Development of Hybrid Ion Imaging System

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ABSTRACT

This thesis reports on a development of hybrid-type ion imaging system for secondary ion mass spectrometry. This system is constructed by a stacked CMOS active pixel sensor (SCAPS), a main chamber, a micro channel plate (MCP) moving unit, a liquid nitrogen cooling unit, and driving electronics for SCAPS. The main chamber is a vacuum chamber with two electrostatic feed-through for mount the SCAPS device. The feed-through is designed to shorten the distance of the SCAPS in the vacuum and the electronics in the atmosphere as possible. The MCP moving unit enables to move a MCP to put on and off on the SCAPS by sliding with a linear drive. The MCP converts an incident ion to thousands of electrons. The liquid nitrogen cooling unit maintains a constant temperature of the SCAPS at –200℃ in order to reduce thermal noises. The electronics includes pulse generation circuit to drive the SCAPS, constant voltage circuit to generate eight kinds of constant voltages to operate the SCAPS, readout amplification circuit to amplify the output signal of the SCAPS, A/D converter to digitize the amplified output signal, and switching circuit to select the operation mode high-speed readout or high-precision readout. This system performs high-speed readout and high-precision readout with a same SCAPS by switching the readout circuits. The data transfer rate of high-speed readout operation is 4MHz/pixel (8.3 frame/second). In this speed, single ion can be detected by amplification using single MCP. The high-precision readout at 20kHz/pixel (3 frame/second) performs low noise correspond to 3 ions, and high dynamic range of 87dB measurement to determine quantitatively isotope ratios. The operation principle of the latest SCAPS and the usages of software are also described.

1. Introduction

Abundances of isotopes in natural materials are distributed over ranges of 6 orders of magnitude. Their isotopic ratios are usually fluctuated less than percent order. Mass spectrometry is commonly used to measure the isotopic ratios. In this method, isotopes are separated depend on their mass. Secondary ion mass spectrometry (SIMS) enables to obtain mass spectra of all elements or isotopes from hydrogen to uranium. SIMS also enables measurements of concentrations of all elements up to ppm-ppb order and of depth profiling of trace elements or chemical compounds about sample surface to few tens of μm. Furthermore, SIMS enables measurements of 2 or 3 dimensional distribution of elements or chemical compounds.

The 2-dimensional imaging by SIMS is achieved by raster-scanning method and stigmatic-imaging method. In raster-scanning method, information of sample surface was obtained by synchronizing the rastering of small focused probe over the sample surface and the detection of signals from the area point by point. The obtained data were reconstructed to 2 dimensional information. The features of scanning method are the high sensitivity and the high dynamic range if we use electron multiplier (EM) for the detector. The spatial resolution of scanning ion beam images is normally determined by the diameter of the primary ion beam on the sample. In order to get a small ion beam size, the use of a low beam current is mandatory. Therefore, long accumulation time is necessary to take a high precision image. Another reprehensible weakness is not to be able to measure all points of imaging area at the same time. Therefore, the status of sample surface may differ from one point to another.

On the other hand, stigmatic-imaging method can use high intensity primary beam. The beam diameter is not restricted spatial resolution of the image because stigmatic ion optics of mass spectrometer determines the resolution. Secondary ions emitted from sample surface were projected as a magnified image on to 2 dimensional detector. Therefore, secondary ion intensity of unit time of a pixel of the image is larger than the case of the raster-scanning method. Measurement time of stigmatic-imaging method is much shorter than that of raster-scanning method when we measure the same area. A stacked-type amplified pixel sensor (SCAPS) is a suitable imaging detector for ions (Matsumoto et al., 1993; Yurimoto et al., 1994; Nagashima et al., 1997, 2000, 2001; Kunihiro et al., 2001), for electrons (Yurimoto and Matsumoto 1996; Yurimoto et al., 1997), and for soft-X-rays (Takayanagi et al., 1995). The SCAPS has high advantages over conventional systems including two-dimensional detection, wide dynamic range, no insensitive time, direct detection of charged particles, a high degree of robustness, and high fill factor (Matsumoto et al., 1993; Yurimoto et al., 1996; Nagashima 2001; Kunihiro 2001; Takayanagi et al., 200).

Present SCAPS ion imaging system was optimized at 20kHz data transfer rates for each pixel due to achieve low noise and high precision operation (Nagashima 2001; Kunihiro 2001). Although this system can measure isotope image in high precision, this system is not suitable for tuning of ion optics of SIMS instruments because of slow transfer rates. Here we develop a hybrid ion imaging system by switching of high transfer rate mode and high precision readout mode using SCAPS detector.

2. Experimental methods

2.1. Description of isotope microscope

2.1.1. Overview

Isotope microscope is an analytical method that has capability of high precision isotope ratio imaging of micro-scale under high mass-resolution (Yurimoto et al., 2003)。This method is achieved by the combination of a stigmatic SIMS instruments and a two-dimensional ion detector SCAPS. The stigmatic SIMS can project the isotope distributions of the sample surface to the SCAPS with keeping the positional information. The SCAPS has excellent sensitivity for several particles in particular to charged particles. The fundamental principle of SIMS is described in §2.1.2 and the SCAPS device is described in§2.2.

2.1.2. Secondary ion mass spectrometry

A Mass spectrometer is an instrumental to measure masses of atoms and molecules by electromagnetism. A mass spectrometer separates and determines mass-to-charge ratio (m/z) of ions after ionization of atoms. The basic parts of any mass spectrometer are composed of three parts, an ionization source, a mass analyzer and an ion detector. There are several ionization methods of atoms. In secondary ion mass spectrometry (SIMS), a focused ion beam with moderate energy (～1-20keV) (referred to as primary ion beam) bombarded a sample surface, and remove materials of the sample by sputtering. The sputtered materials contains ions referred as secondary ions.

A mass analyzer having magnetic sector is commonly used in SIMS. When the accelerated ions are passed through a magnetic field, Lorentz force qvB is equal to centrifugal force mv^2/r,

$$\frac{m}{q} = \frac{Br}{v} \qquad \text{(Eq. 1)}$$

Where the electrostatic charge is q, velocity is v, the radius of ion's circular motion is r.

When the accelerated voltage of ion is V, the ion energy is expressed $1/2mv^2 = qV$. Then (Eq. 1) is expressed as follows:

$$\frac{m}{q} = \frac{B^2 r^2}{2V} \qquad \text{(Eq. 2)}$$

This equation indicates that the radius of circular motion changes with mass where the accelerate voltage V is constant. SIMS uses this effect for mass separation.

Secondary ions have variation of the energy. This variation causes chromatic aberration in the mass spectrometers. The chromatic aberration may be negated by coupling of electric field with the magnetic field. The centrifugal force $mv^2/r = 2qV/r$ of ions with energy qV is equal to electrostatic force $-q$E when E is electrostatic field strength. Then

$$\frac{2V}{r} = -E \qquad \text{(Eq. 3)}$$

Ions with same energy but different to masses can be focused to one spot if we design. Such condition calls "energy focusing". On the other hand, "directional focusing" is a case that secondary ions emitted from a point with several angles are focused to another spot. "Double focusing mass spectrometer" can be performed energy focusing and directional focusing at once.

The condition of double focusing can be realized when an energetic and magnetic analyzers compensate between energy dispersion caused by electric field and momentum dispersion by magnetic field.

SIMS has a capability of two dimensional analysis by primary beam scanning or stigmatic optics of mass spectrometer. The features of primary beam scanning method are the high sensitivity and high dynamic range due to the use of the EM, and the ability to use high mass resolution. A spatial resolution of scanning ion image is determined by a diameter of the primary ion beam on the sample. Cameca NanoSIMS can make several tens nm order primary beam radius using Cs ion source. In order to get a small ion beam, the use of a low beam current is mandatory. Therefore scanning method takes long time to measure large area of sample. Another reprehensible weakness is not to be able to measure the image at the same time with the result that he surface state may change during measurement. In isotope microscope, the spatial resolution is determined by the ion optics of SIMS instruments instead of the diameter of primary ion beam. The spatial resolution of ion optics is typically about 1-2μm.

The ion optics of CAMECA IMS1270 SIMS instruments is shown schematically in Figure 1. A primary ion beam is generated by primary ion source. The primary ion accelerated to 10keV energy and directs to the sample surface. By the bombardment of primary ions, some of particles of sample material are sputtered as secondary ions. The secondary ions forms isotope images onto SCAPS by ion optics through a double-focusing mass spectrometer. TiTech IMS1270 is composed of duoplasmatron (2) and a cesium surface ionization primary ion source (1). The duoplasmatron can generate both O^- and O_2^+ beam. Cesium source can generate Cs^+ beam. Primary ion beam are focused by electrostatic lenses (3) and a primary aperture (4). Cs^+ ion beam can be focused sub-micron size on the sample surface. But the size of beam and the intensity are trade-offs.

A sample stage (5) is biased at a voltage ±10kV, according to the polarity of the secondary ions. The secondary ions are accelerated towards an immersion lens (6) that is a grounded extraction plate as the objective lens. The immersion lens forms an image of the cross-over onto an entrance slit (8) and an image of the sample surface onto a field aperture (10) transfer lenses (7) that magnifies the image. One of the transfer lenses is selected according to the magnifying power. A contrast aperture (9) is very close to the entrance slit in order to reduce the blurring due to geometrical and chromatic aberrations resulting from the various angular divergences of the secondary ions.

The cross-over on the entrance slit is dispersed in energy by a spherical electrostatic analyzer (ESA) (11) and the chromatic dispersion becomes the maximum on an energy slit (13). The energy slit allows only ions of a given bandwidth of energy to pass through to a magnetic analyzer (14). The energy-focused image of the entrance slit is dispersed in mass by a stigmatic magnet, and is focused on an exit slit(15). Spectrometer lenses (12) couple the ESA to the magnet. Hence in double-focusing mass spectrometer, secondary ions are separated according to their mass-to-charge ratio regardless of their energy.

Projection lenses (16) are purposed for imaging onto an ion imaging system (20) either an image of cross-over or an image of sample surface. The removable ESA located after the first projection lens makes possible to switch the beam onto the detection devices instead of the ion imager. The detection devices containing an electron multiplier (EM) (18) and two Faraday cups (FC) (19) can count the amount of ions and are dimensionless detectors. This removable ESA can be used as a mechanical shutter to irradiate the ion imager with the ions or not.

The projected ion image is detected by ion imaging system. The abundances of isotopic ratio in natural material are distributed over the range exceeding 10^6, and the variations are less than % order. Therefore, in order to analyze the isotopic ratio correctly, the ion detection system is needed the two-dimensional isotope ratio imaging with wide dynamic range and permil-precision.

A variety of methods have been used to record ion images. The most popular two-dimensional ion imaging system is composed of microchannel plate (MCP), fluorescent screen (FS), and charge coupled device (CCD) (Hunter *et al.*, 1991). In this system, induced charged particles are detected by the following three steps; First, charged ions are converted to electrons by the MCP. The MCP is essentially an 2-D array of 10^4-10^7 miniature channels, each of which acts as an independent electron multiplier. These channels typically operate at gain of 10^3-10^5 (Wiza, 1979). Next, the electrons are converted to photons by the FS. The FS is a fiberoptic plate coated with fluorescent material such as (Zn,Cd)S called P-20. Luminescence centers in the material are excited by incident electrons and generate photons. Finally, photons are detected by CCD, and output signal being proportional to the intensity of induced photons. Although this system is high sensitive detection system, it is difficult to achieve quantitative isotopic measurement because of 1) non-linearity of the FS in electrons-photons conversion. 2) narrow dynamic range of FS. 3) time dependent change of conversion efficiency of FS and MCP which is caused by damage from electron or ion bombardment. Consequently, the error in isotope analysis was limited to > 5% (Hoppe et al., 2000). In order to solve the problems of FS, resistive anode encoder (RAE) is used in spite of the FS-CCD system (Odem *et al.,* 1983). Although this system has good response against incident ions and good sensitivity to detect single ion, multi event cannot be detected. Thus the effect of deadtime is not negligible. Therefore, it is difficult to measure high and low intensity incident ions at the same time. The system also requires MCP still exists a problem with time dependent change of conversion efficiency.

A stacked complementary metal-oxide semiconductor (CMOS)-type active pixels sensor (SCAPS) has been developed (Matsumoto et al., 1993; Yurimoto et al., 1996; Takayanagi et al., 1999; Nagashima 2001; Kunihiro 2001). The SCAPS has several advantages over conventional systems including two-dimensional detection, wide dynamic range, no insensitive time, direct detection of charged particles, a high degree of robustness and high fill factor. The ion microscope using SIMS can be extended to two-dimensional isotopic ratio imaging with permil-precision by the SCAPS. The isotope microscope is an analysis technique to perform high precision isotope ratio imaging of micro-scale under high mass-resolution by the combination of SIMS and SCAPS (Yurimoto et al., 2003).

2.2. Description of SCAPS device

2.2.1. Overview

In order to realize ideal detection for two-dimensional ion images in the previous section, a solid-state imaging devise, called Stacked AMI, has been proposed by Matsumoto *et al.* (1993). A stacked C-MOS active pixel sensor (SCAPS) described in this section is the latest upgraded style of the devise. Present version of the SCAPS is SUSHI0100. The SCAPS was fabricated in 0.8μm twin-well CMOS technology. The appearance of SCAPS is shown in Figure 2.

2.2.2. Pixel structure

The circuit configuration of a pixel of the SCAPS is shown in Figure 3. The pixel unit consists of a pixel electrode and four transistors: a readout transistor M_{RD}, , a reset transistor M_{RS}, two row selection switch M_{SEL} and M_{xSEL}.

A schematic cross-sectional view of the pixel is illustrated in Figure 4. The pixel electrode made of titanium nitride directly receives charged particles and electrically connects to the elemental device formed on the silicon substrate. The pixel consists of p-MOS readout and n-MOS reset circuit. The size of a pixel is 20μm × 20μm. Because of stacked structure of the electrode, a high fill factor of 88% has been achieved for irradiation of charged particles.

2.2.3. Operational principle

The basic operation of the pixel is as follows. The potential of the pixel electrode

V_{PIX} is reset to the reset voltage PIXVRS using M_{SEL} and M_{RS} by the reset pulse RS and the row selection pulse SEL. This operation is called reset operation. After turned off these switches, integration of the signals of charged particles is started as the voltage V_{PIX}. The charged particles irradiated on the pixel electrode release secondary electrons and ions by interacting with the pixel electrode. The pixel electrode is electrostatically charged through the interactions. The degree of charge on the pixel electrode V_{PIX} is proportional to the number of charged particles. A increase of V_{PIX} from PIXVRS results in the modulation of the output impedance of the read out transistor M_{RD}. Since SCAPS can integrate an electric charge independently for each pixel, SCAPS can detect a charged particle by two dimensions simultaneously. As the input impedance of the readout resistor M_{RD} is very high, the signal charge V_{PIX} can be readout multiple times non-destructively until the following reset operation. After an integration period, the pixel signal is readout using M_{XSEL}.

Figure 5 shows a circuit configuration of the SCAPS pixel array. The SCAPS pixel array is constructed from an imaging area that consists of pixels, a vertical scanner, a horizontal scanner and an analog output buffer. The pixels are arranged to 608 × 576 including 8 × 1 optical black, yielding an image area of 12.00mm × 11.52mm. The pixel addressed (i, j) is shown. The vertical scanner consists of a shift register to increment two row buses, SEL and xSEL. The SEL and xSEL are row selection pulse lines in opposite phase because they consist of p-MOS and n-MOS. Capital letter x indicates opposite phase in this paper. The horizontal scanner consists of a shift register to increment the column number, reset control circuit, and two column buses RS and PIXOUT. RS is a control pulse line of reset operation and PIXOUT is a signal output line.

Readout

The pulse timing required for driving the SCAPS is shown in Figure 6. After the vertical blanking period of 000-030 described in the combination of sequence pattern, VIN pulse turns ON and starts vertical scanner. One horizontal scan consists of a horizontal blanking period of 000-065 and 674-703 described in the upper part of horizontal pulse sequence and an effective pixel readout period of 066-673. A horizontal scanner is started with HIN and the timing pulse to A/D converter is generated until the effective pixel readout period. With the shift register of the horizontal scanner driving pulse HCK1 and HCK2, a number of selected column are incremented. After finishing one horizontal scanning, a vertical scanner is driven by VCK1 and VCK2 to generate row selection pulse VIN.

The analog output buffer of SCAPS is shown in Figure 5. SCAPS has two paths of output, SIGOUT and VOUT. SIGOUT directly outputs the pixel signal. VOUT outputs the amplified signal by an analog output buffer on chip. These output paths can be changed by voltage VBP. When VBP is high, if the input impedance of transistor in analog buffer is sufficiently high, SIGOUT will not be disturbed with VOUT. Because VOUT is always disturbed by SIGOUT, SIGOUT has to be floating or connected to high impedance when VOUT is used.

The drawing of basic readout operation is shown in Figure 7. In the first state (1), the electric charges are integrated for each pixels. When the row selection pulses xSELi and SELi are high level (+5V) in (2), the integrated electric charges of pixels of i row are amplified by M_{RD} and sent to before the column selection switch $M_{PIXOUTj}$. When $M_{PIXOUTj}$ is high level in (3), the amplified signal of (i, j) pixel is outputted to analog output buffer. Thus, pixels are X-Y addressed and SCAPS can outputs two-dimensional image information. This is a rough guideline to readout the pixel signal.

Reset

The reset pulse RS generated in the horizontal scanner using PRS and PLRS controls reset operation (Figure 5). When PLRS is high, RSj is equal to the voltage SRXH. Because SRXH is high voltage for RSj, the pixels of selected row line with SELi are forced to reset. The pulse pattern PLRS(0) in Fig. 6 forces to reset the pixels of selected row line synchronized with VINj. This reset operation is called line destructive readout (LDRO). In this pulse sequence, the pixels of a row line are reset after finishing the readout operation during two pixels time in vertical blanking time. Because PLRS (1) is always high, pixels of each row lines are set to the reset voltage PIXVRS during the row line is selected. In this case, the V_{PIX} is equal to PIXVRS and all pixels of SCAPS are seemed to be forced reset. This reset operation is called full time destructive readout (FDRO). The schematic drawing of LDRO and FDRO operation is shown in Figure 8. When PRS is high and PLRS is low, the pixel is reset synchronized with scanning pulse HINj. This reset operation is called individual reset readout (INDIV). The schematic drawing of INDIV reset opeation is shown in Figure 9. When PLRS (2) and PRS are always low, all pixels of SCAPS are read without reset operation. This readout operation is called non-destructive readout (NDRO).

2.2.4. Characteristics of SCAPS

Linearity

The output characteristics of SCAPS were determined theoretically (Nagashima 2001). They discussed the theoretical relationship about output of SCAPS with the characteristics of MOSFET. The output current, I_{OUT}, of M_{RD} against the pixel voltage in linear region, V_{PIX}, is expressed as follows:

$$I_{OUT} = k\left(V_{PIX} - V_T\right)^2 \qquad \text{(Eq. 4)}$$

$$k = \frac{W}{2L}\mu C \qquad \text{(Eq. 5)}$$

Where V_{PIX} and V_T denote gate voltage and threshold voltage of the M_{RD}, respectively. where W, L, μ, C denote width and length of the MOSFET channel, mobility of electron in the channel, and insulator capacitance per a unit area, respectively. When the load resister R_L is added to readout, the output signal voltage VOUT can be expressed as follows (Nagashima et al., 1997). Ideal transistor

$$V_{OUT} = V_{PIX} - V_T + \frac{1}{2kR_L} - \frac{1}{2kR_L}\sqrt{1 + 4kR_L\left(V_{PIX} - V_T\right)} \qquad \text{(Eq. 6)}$$

Then the linearity correction (Nagashima et al.,2001 SIA) based on a realistic MOS model, namely α-power law MOSFET model (Sakurai and Newton, 1990; Bruna and Otten, 1997) was proposed to obtain ion counts from outputs of SCAPS device. The proposed equation is as follows;

$$N_i = N_R\left(a_1 V_{OUT_i} + a_2 + \left(a_3 V_{OUT_i} + a_4\right)^{a_5}\right) \qquad \text{(Eq. 7)}$$

where N_i are the integrated ions from time t_0 to t_i and N_R are the integrated ions from t_0 to t_R.. V_{OUTi} are the output voltage of SCAPS integrated from t_0 to t_i. a_i are fitting parameters. And a normalized parameter, η, is defined as,

$$\eta_i \equiv \frac{N_i}{N_R} \qquad \text{(Eq. 8)}$$

SUHSI has good linearity in a region below an output saturation level of 2.0V corresponding to 5×10^4 ions at the Al^+ incident ion with 10keV energy at liquid nitrogen (LN2) temperature (Takayanagi et al., 2003) .

Noise

The noise analysis of SCAPS was performed (Takayanagi et al., 1999 and 2003; Kunihiro 2001Nucl). The noise of SCAPS includes fixed-pattern noise (FPN), reset noise, read noise, and shot noise. FPN is independent on the signal and caused in particular by variations in the pixel sensitivity between pixels. The reset noise occurs during the reset operation. FPN and reset noise can be reduced using nondestructive readout correlated double sampling (NDRO-CDS) (Takayanagi et al., 1999,2003; Kunihiro 2001). First, the imager is reset by turning the reset transistor M_{RS} on, and an offset signal that includes FPN and reset noise is readout nondestructively and transferred to a frame memory. After an integration period, the signal is readout again. Since the reset noise components in both images are identical, it can be suppressed by subtracting the offset image. Read noise is 0.1mV reffered to the pixel electrode voltage corresponding to 9e-. Twin well pixel structure was adopted to suppress dark current at and expand wide dynamic range. Because almost of noise source are suppressed, 1/f noise becomes the dominant noise source of SUSHI. The 1/f noise has a power-spectrum that is inversely proportional to frequency (Johnson 1925). Noise floor of the SCAPS system including 1/f noise was measured to be 85 μV_{rms} at imager output that equivalently corresponds to about two input ions.

2.2.5. Conclusion

The dynamic range expressed as follow equation $D = 20 \log S/N$ is 87dBThe result of various improvement, SUSHI comes to have several advantages over conventional SCAPS, including low leakage current, low dark current, and low read-out noise added to the conventional futures, including two-dimensional detection, wide dynamic range, no insensitive time, direct detection of charged particles, a high degree of robustness, and high fill factor (Matsumoto et al., 1993; Yurimoto et al., 1996; Nagashima 2001; Kunihiro 2001; Takayanagi et al., 2003; Yurimoto et al., 2003).

2.3. Description of hybrid ion imaging system

2.3.1. Overview

The SCAPS ion imaging system developed by Nagashima and Kunihiro was optimized at 20kHz data transfer rates for each pixel due to achieve low noise and high precision operation (Nagashima 2001). Although this system can measure isotope image in high precision, this system is not suitable for tuning of ion optics of SIMS instruments because several frames per second must be obtained to monitor the ion images in real time. Therefore, another SCAPS system was developed that SCAPS was drived with high-speed. This high-speed system uses a single MCP to amplify the signals for increasing signals per readout time.(Sakamoto 2001). The features of conventional systems are described follows.

2.3.2. High precision system

The high precision system is composed of the host computer, the SCAPS controller, driving unit, and the SCAPS driver. The host computer controls all systems, and communicates with the SCAPS controller. The SCAPS controller plays the role to collect and store the readout signal from SCAPS and to control the setting of the SCAPS driver. The driving units named EPGS (Enhanced Pulse Generator for SCAPS) makes the driving pulse in order to drive the SCAPS by receiving the setting data from the controller and sends to the SCAPS through the SCAPS driver. The SCAPS driver sends the driving pulses to the SCAPS and transmits the digital control signal from the controller to various voltages such as power for the SCAPS, reset bias, readout voltage. The SCAPS driver includes a low-noise amplifier to amplify the output signal from SCAPS, 16-bit analog-to-digital (A/D) converter unit to digitize the amplified signal, the low pass filter typical value of time constant is calculated to 21.9kHz and the offset circuit to adjust the offset level for the input range of A/D converter.

2.3.3. High speed system

The high speed system is composed of MCP, the host computer, driving unit, the

QV SCAPS driver, and the high speed A/D converter PCI-6111E with BNC2110. The readout speed is 9.35 frame/sec (4MHz/pixel) and the signal is digitized by 12-bit analog to digital converter (ADC). In order to adjust instrument, it is necessary to acquire images on real time. Because the amount of integrated signal per frame decreases as read-out speed increases, incident ions are amplified by the MCP, and the converted electrons are detected by SCAPS. The potential across the MCP could be varied between 0 and 1100V, and the rate of amplification corresponds to $0\text{-}10^3$.

2.3.4. Hybrid system

In this paper, the hybrid type ion imaging system that performs high-speed readout and high precision readout with the same SCAPS device was developed. A schematic block diagram of a hybrid ion imaging system is shown in Figure 10. Hybrid system consists of hybrid SCAPS chamber includes a MCP movement unit and a liquid nitrogen Dewar, electronic circuits and host computers.

2.4. SCAPS chamber design

2.4.1. Overview

When designing the hybrid SCAPS chamber, the following points were noted. (1) The MCP must be detachable in order to perform high precision readout and high-speed readout by the same SCAPS device. (2) Short connection length distance between a device and an external amplification circuit should be achieved in order to avoid attenuation of a signal, and to send good pulse shapes at a high-speed drive. (3) It must keep the temperature of the device constant at LN2 temperature due to high precision read-out. In order to achieve these points, the hybrid SCAPS chamber was decided to be composed with the following three parts; main chamber, MCP movement unit, and cooling unit. The photograph of components is shown in Figure 11-(a). The overall view of hybrid SCAPS chamber is shown in Figure 11-(b).

2.4.2. Main chamber

The main chamber consists of a vacuum chamber and a SCAPS chamber. A drawing of the SCAPS chamber is shown in Figure 12. The SCAPS chamber has an ICF-34 fitting for linear drive to introduce a MCP movement unit. The cooling unit consists of LN2 Dewar and cold finger is welded. The SCAPS chamber can be attached to the vacuum chamber using an ICF-203 fitting. The MCP movement unit and the cooling unit are described in §2.4.3 and §2.4.4 respectively. Two electrostaical feed-through are implanted. A drawing of the feed-through is shown in Figure 13. The feed-through connects between the SCAPS in a high vacuum and the electric circuit in the atmosphere. This feed-through are specially designed in order to shorten the distance of SCAPS in the vacuum and the amplified circuit in the atmosphere as possible. It is also embedded two MHV terminals and two BNC terminals supplying high voltages to MCP and using for low-voltage supply, respectively.

The drawing of vacuum chamber is shown in Figure 14. The vacuum chamber plays a role as a interface of the hybrid SCAPS system with the SIMS instrument using ICF-70. They are divided by a gate valve (VAT, Mini UHV gate valve 01032-CE01). A turbo pump is attached with ICF-114 to isolate vacuum between SIMS and the chamber. Conventional SCAPS system can also be attached to the vacuum chamber with ICF-114. The cylinder type liner drive is adapted to the conventional SCAPS system for introducing the SCAPS to the image plane of the SIMS instrument. This linear drive can drive up to 50mm. Thus, the SCAPS of conventional system can be positioned to the image plane for detecting the ions or park position not to be irradiated the ions. This SCAPS is used in the conventional SCAPS to measure. But, in hybrid SCAPS system, the SCAPS device of the conventional SCAPS system is not used and positioned to park position. In order to observe the physical condition of SCAPS without venting the chamber, a view port was installed. The view port was designed with ICF-70 to observe the device as in the vicinity as possible.

2.4.3. MCP movement unit

The MCP movement unit has essential role for hybrid SCAPS system to put on and off the MCP onto SCAPS device. Because the SCAPS device is fixed on the

SCAPS chamber, the MCP movement unit slides on the SCAPS device by the linear drive (VG, ZLDS950). The movement is up to 50mm length. The MCP movement unit consists of several delicate components as follows: MCP, SCAPS mask, front electrodes and back electrodes for MCP, and foundation called base fork. They are made of stainless steel. The assembly diagram of MCP movement unit is shown in Figure 15.

A MCP is an array of 10^4-10^7 miniature electron multipliers oriented parallel to one another (WIZA 1979). We use BURL as the MCP. The Channel diameters using in this thesis are 10μm, center to center spacing is 12μm, and have length to diameter ratios 60:1. The thickness is 0.61mm. Channel axes are biased at a 12° angle to the MCP input surface. The surface area of the openings called open area ratio is about 58% of the total surface, so more than half of the incident particles strike the solid glass surface and do not enter a channel. The gain of channel electron multipliers is given by many authors (Adams et al., 1966; WIZA 1979). The most simply theoretical equation is expressed with a normalized length α=L/d where L is the channel length and d is the diameter.

$$g = \exp(G \cdot \alpha) \qquad \text{(Eq. 9)}$$

where g is the gain and G is the secondary electron yield depended on the material of channel wall (Hamamatsu photonics). The gain is limited to 10^3-10^5 by the ion feedback. Ion feedback is the drift back of ions to channel input and producing additional secondary electrons by the ions after pulses. These ions are produced by electron collisions with residual gas molecules in the channel and with gas molecules desorbed from the channel walls under electron bombardment.

The MCP is installed at 1mm above SCAPS surface. The MCP is operated to be applied potential difference of up to 1200 V. The higher voltage is applied by four leaf springs spot-welded to the front electrode (Figure 16). The leaf springs have also a role as holding down on the MCP. The lower voltage is applied to the MCP by the back electrode (Figure 17). The back electrode has same potential with SCAPS mask (Figure 18). The back electrode and the SCAPS mask play a role to absorb secondary electrons emissions from the SCAPS surface as a result of the interaction on incidences charged particles. The typical voltages are +15V in high speed readout and +50 V in high precision readout. These voltages are applied to electrodes by MHV terminals. SCAPS mask also plays a role to protect the bonding wires of the SCAPS device from incidence charged particles. This assembly is attached to linear drive with base fork (Figure 19).

These metallic parts are insulated by aluminum spacer (Figure 20).

2.4.4. Cooling unit

To reduce thermal noise in each pixel during ion irradiation and during the time waiting for the readout, it is necessary to cool the SCAPS by liquid nitrogen. The cooling unit is consists of LN2 Dewar and cold finger. The cooling unit is shown in Figure 11-(b). The LN2 Dewar is attached to SCAPS chamber by two pipes between LN2 Dewar and the hybrid SCAPS chamber. An upper large pipe supports the weight of LN2 Dewar and improves in the degree of vacuum in LN2 Dewar. Another double pipe combines with the hybrid SCAPS chamber with a slope. The inside pipe is filled with LN2 prolonged from LN2 Dewar and is covered by a outer vacuum pipe. The SCAPS device is mounted on the cold finger made of Cu (14mm×14mm×6.5mm) that is attached the top of the double pipe. The fluctuation of temperature is the severe problem in high precision analysis because the output of the SCAPS depends on the temperature. In order to cool the SCAPS and to maintain the temperature constant, it must be adhesion the Cu and the SCAPS to tight. But, there are some difficulties as follows. In conventional SCAPS system, there was only SCAPS mask on the SCAPS device. So, the SCAPS and cooling rod could be pressed down from the upper and lower sides. But in the hybrid SCAPS system, the MCP movement unit slides onto the SCAPS device. The power pressed down from a top of the SCAPS device cannot be applied. Movements of the MCP movement unit on the SCAPS misalign the SCAPS and Cu by the friction between the MCP movement unit and the SCAPS surface both. Owing to the thermal contraction of Cu at LN2 temperature, the SCAPS and Cu do not adhere. Then, it decided to use fixing brackets. The drawings and photographs of the fixing brackets is shown in Figure 21. SCAPS and Cu are adhesion by fastening the turnbuckles and crimping terminals soldered to pins of SCAPS with a screw.

2.5. Circuit design

2.5.1. Overview

In order to operate SCAPS, the following electronic circuits are essentially required.

I. A pulse generation circuit to generate the driving pulses for horizontal and vertical scanner of SCAPS.

II. A constant voltage circuit to generate eight kinds of constant voltage for the SCAPS, such as the reset voltage and the readout voltage, etc.

III. A readout amplification circuit to amplify the output signal from the SCAPS in order to be come high tolerance for noise.

IV. An A/D converter for digitizing the amplified output signal.

The high precision system and high speed system have own electric circuits separately. In order to integrate these SCAPS systems, hybrid SCAPS system was developed. Block diagram of electronic circuits is shown in Figure 22. (1) The driving pulse can be switched by driving pulse generator named Enhanced pulse generator for Hybrid (EPGH) in hybrid SCAPS system. The driving pulse of high speed readout is generated by EPGH. When SCAPS is operated in high precision system, the driving pulse generated by Enhanced Pulse Generator for SUSHI (EPGS) is pass through the EPGH to SCAPS. (2) The constant voltages are generated by the voltage supply circuits (DC) of each system and switched by two mechanical relays (RELAY) (Omron, G6A-474P). The output path of SCAPS, SIGOUT or VOUT, is changed by changing constant voltage by the analog buffer VBP shown in Figure 5. The high-speed system uses SIGOUT and high precision system uses VOUT. The different output paths of SCAPS are described in §2.2.3. (3) The output signal is amplified by amplification circuit (AMP). The suitable operational amplifiers (Op amp) are adopted to amplify the output signals in each system. The signal of high speed system is amplified by a high speed Op amp (AD844, Analog Devices) after conversion from the output current from SIGOUT to voltage using a low noise Op amp (AD797, Analog Devices). The high precision system uses an ultra low noise Op amp (Analog Devices, SSM-2017). (4) The amplified signals are digitized by analog-to-digital converter (ADC). The A/D converter is selected from the characteristics of the digital resolution and the speed. The ADC of high precision system was established in APS Driver with 16-bit resolution. The analog signal are divided into 2^{16} analog to digital unit (ADU) in the range of input voltage through low-pass filter consisted of RC circuit. The ADC of high speed system uses 12-bit multifunction data acquisition board (PCI6111E, National Instruments). This board is installed into PCI bus of computer and connected to the BNC adapter (BNC2110, National Instruments). The physical connection layout of hybrid SCAPS system is shown in Figure 23.

2.5.2. Electronic circuit for high precision system

The main components of high precision system were developed by Nagashima and Kunihiro. The components are a host computer, SCAPS controller, driving unit, and SCAPS driver. The host computer bears the control of all systems, and communicates with the SCAPS controller. The SCAPS controller plays the role to collect and store the readout signal from SCAPS and to control the setting of the SCAPS driver. The driving units EPGS makes the driving pulse in order to drive the SCAPS by receiving the setting data from the controller and sends to the SCAPS through the SCAPS driver. The SCAPS driver sends the driving pulses to the SCAPS and transmits the digital control signal from the controller to various voltages such as power for the SCAPS, reset bias, readout voltage. The SCAPS driver includes analog-to-digital (A/D) converter unit and the analog signal is digitized after the output signal from SCAPS is amplified, and the offset level is adjusted. The digitized signal is outputted to the controller. The output mode is VOUT that output the signal as voltage.

2.5.3. Enhanced pulse generator for Hybrid (EPGH)

Takuya Kunihiro did the initial design of driving pulse generator for SCAPS. The pulse generator has been upgraded with the development of SCAP. The pulse generator of high precision system is EPGS. The EPGS has a flag to whether to start scanning the frame or not, to scan with or without generating the synchronized A/D conversion timing pulse, to select the reset operation (FDRO, LDRO, NDRO), and to change scan speed (10kHz, 20kHz, 40kHz, 80kHz, 125kHz, 250kHz, 500kHz, 800kHz, 1MHz, 2MHz), to select the pixel area to read (FULL [608 pixels × 576 pixels], FULL QUICK [608×576], Mabiki [304×288], Mabiki [152×144], Mabiki [76×72], Center

[456×432], Center [304×288]). FULL, Mabiki, Center mean to read all pixels, one pixel every some pixels, center area of imager respectively.

In a hybrid SCAPS system, driving unit EPGH based on EPGS was developed. The layout of EPGH is shown in Figure 24. EPGH is composed of (1)Electrically Erasable Programmable Read-Only Memory (EEPROM, Altera, EPC1213), (2) Hardware reset switch in order to stop runaway operation, (3)the basic clock generation circuit using the 32MHz crystal oscillator, (4)field programmable gate array (FPGA, Altera, FLEX8000), (5) (6) (7) (8)buffers and line drivers for input and output pulses, respectively , and (9)voltage supply. The program described by VHSIC hardware description language (VHDL) is burned into EEPROM. All the logic development is made by the programmable logic development system, Max+Plus II (Altera). The program is downloaded to FPGA when voltage supplied. VHDL is listed in Figure 25. EPGH has simple control flags with compared as EPGS whether to scanning the frame or not, to select the reset operation (FDRO, LDRO, NDRO), to change scan speed (20kHz, 500kHz, 2MHz, 4MHz), and to select high precision readout or high speed readout. EPGH can switch between the pulses of high precision readout and high speed readout. In high precision readout, EPGH pass through all of the input pulses generated by EPGS. In high-speed readout, EPGH generates not only driving pulses but also synchronously driving pulse timing for the A/D converter. The A/D conversion timing pulses are outputted to A/D converter from EPGS. The pulse timing is described in §2.2.3. It is possible to generate required clock pulses by both of read-out systems only by EPGH, without using EPGS. However, for using EPGH and EPGS together, it is from the following reason. The present hybrid SCAPS system uses a host computer that is different by high-speed readout and high precision readout. When generating a pulse only by EPGH, only one of host computers has the role that controls a clock pulse. Measurement and adjustment may become impossible when fault happens during measurement or adjustment at the computer currently controlled.

The EPGH is also designed to be controlled by the host computer through the PCI-6111E. The simple control system is used for control of EPGH. The control signal outputted from eight digital I/O of PCI-6111E is inputted into direct FPGA via BNC-2110. EPGH can controlled as follows; readout mode, start or stop scan, scan speed, FDRO or LDRO or NDRO, the pixel set to read. However, in the present EPGH, (2)a hardware switch is used to change of read-out mode by the same reason as using EPGS together. Typical settings are that scan speed is 4MHz, reset mode is LDRO, and the pixel set to read is all pixels.

2.5.4. SCAPS voltage supply (DC)

The SCAPS needs eight kinds of voltages such as the power for the SCAPS, the reset bias, the drain voltage, and the substrate voltage. The values of these voltages are shown in Table 1. VLS is shield electrode voltage, DSCH is pre-charge bios voltage for column signal line, SRXH is high level voltage of pixel reset pulse RS, SRXL is low level voltage of pixel reset pulse RS, VBP is bios voltage for analog output buffer, PIXVRS is pixel reset voltage, PIXVD is drain voltage of pixel. The layout of circuit is shown in Figure 26. These voltages are generated in (2) SCAPS voltage supply part and sent to SCAPS with the feed-through (Figure 13) through (3) relay circuit. These relays can change the voltage set for high precision readout generated by APS Driver and the voltage set for high-speed readout generated by this circuit. The hardware switch uses for changing, The read-out mode is used to change the voltage set.

2.5.5. Amplification circuit (AMP)

The analog signal from the SCAPS is converted to voltage in (4) I-V circuit and amplified to improve signal to noise ratio in (5) amplification circuit and adjusted to the input range of A/D converter in (6) voltage source follower in Figure 26. In high-speed readout, the analog signal from the SCAPS is outputted as current. The outputted current is transformed into voltage by the current-voltage conversion circuit using a high speed monolithic operational amplifier AD844. A conversion factor is dependent on exchanging resistor. For example, if the resister is 10kΩ, the theoretical value of a noise produced in this circuit is 0.3% from the specification of AD844. The signal changed into voltage is amplified 9966.8 times by the differential amplification circuit. The voltage follower using AD797 generates the offset voltage of a differential amplification circuit. Offset voltage adjusts to the range of the input of A/D converter.

2.5.6. Analog to digital conversion units (ADC)

The amplified output signal from the SCAPS is converted to digital signal by A/D converter of PCI-6111E. PCI-6111E is a multifunction analog, digital, and timing I/O device for PCI bus computers. PCI-6111E features a 12-bit ADC per channel with two simultaneously sampling analog inputs, eight lines of TTL-compatible digital I/O, and two 24-bit counter/timers for timing I/O. The Max sampling rate is 5MS/s. It has gains of 0.2, 0.5, 1, 2, 5, 10, 20, and 50, and is suited for a wide variety of signal levels. The resolution of A/D converter is 12bit. Typically, the gain is 1.0V and the input range is -10 to +10 V. In this condition, the precision of A/D converter is 4.88 mV (PCI-6110/6111 User Manual, November 2000). The relationship between the input voltage and digital number is expressed as follows,

$$N = -Vin \times \frac{4096}{V_{range}} \qquad \text{(Eq. 10)}$$

where N is digital number converted by A/D converter, V_{in} is input voltage, and V_{range} is the range of input signal voltage typically 20. The PCI6111E also plays a role as EPGH controller using the function of digital output.

The BNC-2110 is a desktop and DIN rail-mountable BNC adapter to connect directly to data acquisition device. BNC-2110 can measure floating and ground-referenced analog input signals. In the ground-referenced source measurement, it is difficult to avoid ground loop. It uses by making sauce into floating. In the floating source, the amplifier negative terminal connects to ground through a 5 kΩ resistor in parallel with a 0.1 μF capacitor.

2.6. Software design

2.6.1. Overview

Since high-speed readout uses a different system from high precision readout, a software named ION MONITOR is developed. ION MONITOR was written by the LabVIEW graphical programming language (National Instruments). The reason why we choose as a software development system, the graphical interface and abundant libraries enable us to make the programming much easier and enhance our ability to advance and reconfigure the software. LabVIEW is the compatibilities with the software of conventional SCAPS system and with the software controlling CAMEMA IMS-1270 and the ease of development. Moreover, LabVIEW can use the driver libraries of PCI-6111E and BNC-2110 called NI-DAQ (National Instruments).

In conventional SCAPS system, the software named APS-VIEW was developed to control the system by Kunihiro and Nagashima (2001). SCSI is used as an interface of a host computer (Apple Macintosh) and APS Controller. Because there are no libraries of SCSI in LabVIEW, low level SCSI libraries using extension code named code interface node (CIN) is also developed in Macintosh Code Warrior (Metrowerks) in C language by Kunihiro. With development of new designed SCAPS, the software named SUSHI-VIEW was upgraded for APS-VIEW to drive the SCAPS device by Kunihiro and Nagashima. High precision readout system is controlled with SUSHI-VIEW.

In this section, the functions and usages of ION MONITOR and SUSHI-VIEW are described.

2.6.2. Software for high speed readout

In order to adjust ion optics of SIMS instruments, a software called ION MONITOR is developed to monitor the ion image in real time, which means rapid data read for pixels and displaying the ion image on a monitor screen. It developed with attention to the following points. Since all users of SIMS instruments will use it, the usage and operation have to simple and stable. Because restrictions of read-out speed depended on the drawing performance of a computer, this software thinks speed is more important than functions. The interface of the ION MONITOR is shown in Figure 27.

ION MONITOR is consisted of the controller of EPGH, image display and data acquisition function. The controller of EPGH has flags whether to (5)start scanning or (6)not, to change readout speed [20kHz][250kHz][500kHz][1MHz][2MHz][4MHz] and reset operation [FDRO][LDRO][NDRO] (hidden in this figure). Typically, the readout speed and reset operation are fixed at 4MHz and LDRO. The controller of EPGH outputs the command signal from digital output line of PCI-6111E as ON (5V) or OFF (0V), and is inputted into FPGA via BNC-2110. The pixel data can be easily acquired using the NI-DAQ libraries prepared by LabVIEW. It is necessary to make a computer recognize BNC-2110 to be PCI-6111E by hardware configuration utility software before to use the libraries. The length of buffer size is shown in (11)indicator. The buffer can be cleared by (12)an empty button. The value of pixels is expressed by the color depth with a color of 8 bits (256 colors) in an (1)image display. The (14)scales of the image display can be calculated (9)automatically and can be treated in both (7)a linear or a logarithm scale. The color table can be changed by (15)color table selection switch. (2)(3)Several markers are available to store important positions for adjustment of instruments such as the center of field aperture or edge of exit slit. Because the output signal of SCAPS includes fixed pattern noise (Kunihiro et al., 2001), operation of compensation is required to subtract a current frame from a frame acquired in the state that is not irradiated with ions named dark frame. The dark frame is memorized by (8)getRST switch. A (13) selection switch selects which current or subtracted image shown on the image display.

ION MONITOR operates as follows.

I. Initialize a hardware driver and all parameters.

II. Stop scan, and start scan after clearing a buffer by reading and discarding all the data that has accumulated in the buffer. After operation of SCAPS is stabilized,

III. Read length of a buffer until the data for one frame (576×608 pixels) is accumulated at a buffer.

IV. If the data for one frame is accumulated at a buffer, the dark frame saved in the memory from the current transferred frame is translated. The data is displayed on image display.

V. Return to III. If a reset button is pushed, it will return to II.

However there are many buttons on the interface of ION MONITOR, the typical usage needs (4)RESET button only. RESET button run batch process including II, III, IV.

2.6.3. Software for high precision readout

The interface of SUSHI-VIEW is shown in Figure 28. SUSHI-VIEW consists of eight programs and one utility program. The functions of each programs are as follows; (1) launch other programs, (2) a controller of EPGS, (3) a controller of APS Driver, (4) a controller of FIFO memory system, (5) set global variables for each programs, (6) a real-time image viewer, (7) a data logger, (8) calculator of an apparent isotopic ratio, and an utility (9) cycle the magnetic field through a series of calibrated mass peaks. (1)The launcher start-up first and turn on and off the other programs. (2)The controller of EPGS has a flag to whether to start scanning the frame or not, to scan with or without generating the synchronized A/D conversion timing pulse, to select the reset operation among [FDRO][LDRO][NDRO][INDIV], to select scan speed among [10kHz] [20kHz] [40kHz] [80kHz] [125kHz] [250kHz] [500kHz] [800kHz] [1MHz] [2MHz] and to select the pixel area to read among [Full 608×576] [Full Quick 608×576] [Mabiki 304×288] [Mabiki 152×144] [Mabiki 76×72] [Center 456×432] [Center 304×288]. However the scan speeds up to 250kHzcan be applied for image acquisition because of the upper limit of throughput speed of the amplifier of APS Driver. The series of pixel area [Full][Mabiki][Center] means to read full pixels, skip lines, read center area. [Full Quick] means to read full pixels with no blanking time. (3)The controller of APS Driver sets the reset voltages for SCAPS and the offset voltage for the amplifier in the APS Driver. The SCSI commands are activated only when the operator changes the input of these controllers. Since the host computer was changed into Sun Ultra-80 from Macintosh, the SCSI driver for Sun is newly incorporated in SUSHI-VIEW. (4) The controller of FIFO activate a SCSI command to refer the length counter in the FIFO memory system every 0.1 s. After the length counter becomes larger than the number of pixels in one SCAPS frame, the signal data of one SCAPS frame will be transferred to the host computer from the FIFO memory system by the acquire commands of SCSI. The transferred data is saved to a file, if necessary to the save path defined by (5) setting global variables available from any programs. The transferred data is displayed by (6)a image display. The value of pixels is indicated by the color depth with a color of 8 bits (256 colors) in an image display and the quantitative line profiles in the vertical and horizontal direction are also shown. The operator can dynamically change the location of line profiles by moving a cursor. The scales of the image display and the line profiles are automatically calculated and can be treated by either a linear or a logarithm scale. Moreover the real-time image viewer has five view mode, [CURRENT], [RESET], [dRESET], [CRNT-PREV] and [MATH]. [CURRENT] display the raw data of current acquired image. [RESET] display a stored frame in computer memory named reset frame using [Get Rst] switch. [dRESET] display a calculated image subtracted reset frame from current frame. This mode is used to view a total accumulated ion image to get reset frame at the early of NDRO operation. [CRNT-PREV] display a calculated image subtracted the last frame named previous frame from current frame. This mode is used to view the current incident ion image. [MATH] display an apparent isotopic ratio computed by (8) math program using natural isotope ratios at once. (7)Averager logs and plots average values of an area defined by (5)setGlobals. (8)LoopMass can cycles the magnetic field through a series of calibrated mass peaks from in the order of list from top in order to minimize the effect of the hysteresis on the magnetic field (Figure 1-(14)) of SIMS instruments and to stabilize the reproducibility of a peak jump.

The typical measurement sequence using SUSHI-VIEW is as follows.

I. Start (2)ctrlEPGS、(3)ctrlDriver, (4)ctrlFIFO、(5)setGlobals、(6)FrameView、(7)Averager from (1)Launcher.

II. Initialize and check the operating condition of APS controller, APS Driver and EPGS as follows. Set [RST_MODE]: [LDRO], [CLK_SPEED]: [20kHz], [SCAN_MODE]: [FULL (608*576)] in (2)ctrlEPGS. This operation command EPGS to drive SCAPS at LDRO reset mode and 20kHz/pixel readout speed and reading full pixels. Set [BIAS]: [205], [Supress]: [80] in (3)ctrlDriver. This operation commands APS Driver to set reset voltage at 1.0V and offset voltage at 3.75V. Click [EmptyFIFO] in (4)ctrlFIFO. This operation command APS controller to empty backlog of noise occurred when turning on the power in the FIFO memory.

III. Turn on the synchronized A/D conversion timing [ADP] first, and second turn on scan [SCAN] in (2) ctrlEPGS. Scan starts and pixel data begins to be accumulated to FIFO memory.

IV. After the length counter [LFIFO/pix] in (4)ctrlFIFO becomes a total number of effective pixels, the signal data of a SCAPS frame will be transferred to the host computer from the FIFO memory system. The value of pixels is expressed in the depth with a color of 8 bits (256 colors) in (6)FrameView.

V. Reset operation is executed several times to reset the integrated signals completely before measurement. It is necessary to wait the stability of SCAPS after reset operation. The stability of SCAPS is monitored by (7)Averager. To facilitate this waiting process, reset sequences [Seq] were built into (2)ctrlEPGS to change the reset mode to click [Jump_to] according to the stability of SCAPS. Select the presets of reset sequence from [Seq] from among [Exit], [FDRO, LDRO, NDRO], [LDRO, NDRO], [NDRO Beam Monitor] in (2)ctrlEPGS. [Exit] is force escape the reset sequence, [FDRO, LDRO, NDRO] start by FDRO. After the stability of SCAPS achieves the preset value, shift to LDRO. The preset values are hidden in (2)ctrlEPGS. NDRO starts after the achievement in LDRO and break through the stability level enough for high precision measurement typically 2.5 ADUrms, the reset sequence shift to [Exit] to end. As cooled SCAPS has vanishing low dark current and leakage under NDRO operation, the measurement condition is ready. When the reset mode will be changed manually, select from [RST_MODE] in (2)ctrlEPGS.

VI. When SCAPS is stabilized, set a save path of acquisition data [Set_Path] in (5)setGlobals.

VII. Cycle the magnetic field through a series of calibrated mass peaks by (8)LoopMass. At the end of the cycle, mass is fixed by specified isotope. The list of calibrated mass should be formed with order of the small mass number in order to cancel the hysteresis. The number of loop time can be changed.

VIII. Next operation is to irradiate SCAPS with ions. The timing of this operation needs a tips. During the preparing for measurement, the removable ESA (Figure 1-(17)) intercept ions from SCAPS as mechanical shutter and introduces ions to EM or FC. It is preferable to irradiate SCAPS at the beginning of SCAPS frame in order to make all pixels as same condition as possible. There is time rag to move the removable ESA from the position to lead ions into EM, FC to SCAPS. Consequently, the best timing to move the ESA is the time to accumulate 280000 pixels of last frame. Ions start to incident onto SCAPS at the same time to begin a frame later on moving the ESA by switch to Slit image mode with SIMS controller from EM or FC.

IX. After acquisition of new frame starts, turn on the save button [AutoSave] in (4)ctrlFIFO to save measurement data. The data format is unsigned 16-bit binary.

X. After the measurement as acquire, move the removable ESA to EM, FC position, start the reset sequence to click [Jump_to] and turn off the [AutoSave]. If measurement is continued, return to VI.

XI. When measurement is finish, turn off the scan switch [SCAN] in (2)ctrlEPGS. Click the red LED on (1)Launcher to close (2)-(7) window and close (1)Launcher from menu bar of window.

2.6.4. Assistant software for measurements

Automation software

The software named APS-CHAIN was developed to automate the typical measurement sequence of SCAPS system. This program allows the operator to run several analyses onto different isotopes in a batch mode. APS-CHAIN uses the function of SUSHI-VIEW and CIPS. In order to cooperate CIPS and SUSHI-VIEW, several changes were added to SUSHI-VIEW. The Chained analysis program interface consists of two dialog boxes: (a) One isotope analysis and (b) Chained one frame analysis. They are shown in Figure 29. (a) One isotope analysis runs a set of one isotope measurement. (b) Chained one frame analysis runs a set of several isotope measurement on one area.

After adjustment of SIMS instruments is finished, the operator can measure isotope images only to select the isotopes, the number of frames, necessity of reset. The number of frames is determined by requirement for the projected precision from natural isotope abundances for the analysis, and decide whether reset or not before measuring in order to measure within the limits of a dynamic range.

(a) aps_chain_isotope operates as follows.

XII. Define a list of isotopes to measure (hidden in the figure, but it is same as Figure 28-(9). This list is used for (1) selecting measuring isotope and Loop Mass. Then, this list of isotope to measure is also needed to be formed with order of the small mass number to cancel the hysteresis.

XIII. Select (1) isotope to measure, input (3) number of frames to acquire, decide existence of reset flag (hidden in (a)) and set save path in (10) Base_Path. And set reset sequence in ctrlEPGS (Figure 28-(2)). Finally click (4) start button in Figure 29. Measurement is automatically processed after following steps.

XIV. Reset SCAPS according to a reset sequence selected by [Seq] field in (2) ctrlEPGS in Figure 28 described in VI of SUSHI-VIEW operation if the reset flag is ON. And wait until the output of SCAPS is stabilized.

XV. Cycle the magnetic field through a series of calibrated mass peaks with loop mass software. The number of loop time is fixed only once. At the end of the cycle, mass stop at specified isotope.

XVI. Count total number of ions detected by (8) FC and display at (9) indicator. The detector to measure the total counts of ions is fixed in FC. Because EM detector is damaged by strong incident ion beam up to 10^5cps, EM is not used on automated measurement to protect detector

XVII. Generate directory to save data based on the isotope name under (4) the established path in II.

XVIII. The detector of SIMS instruments is changed into SCAPS from FC by shifting the removable ESA (Figure 1-(11)), and secondary ion is irradiated on SCAPS. This timing is same to the operation §2.6.3 of IX.

XIX. Accumulate ions until the specified frame number and save the acquired data to the generated path in V. with every end of acquisition of a frame.

XX. Change detector into FC from SCAPS.

XXI. If measurement is finish, turn off the primary ion beam and do as XI. of §2.6.3. If measurement is continued, return to I.

(2)aps_chain_frame makes aps_chain_isotope a function, and expands into measuring multiple isotopes in one analysis.

(2)aps_chain_frame operates as follows.

I. Input (11)base of save path, (13)reset flags, (14)isotopes to measure, (15)numbers of frames each isotope, (16)VALID or not, and (16)the list for loop mass.

II. Click (12)start button to run aps_chain_isotope through a series of specified isotopes.

Transformation of coordinate systems

In SIMS instrument, we target measuring area in a sample on a sample stage by optical image acquired by CCD on real-time. Because it can be difficult and time consuming to set the exact position at micron meters that were determined to measure using different instruments, especially BSE image, a software was developed to transform relatively easily between the coordinate systems of the different sample stages. Affine transformation was adopted assuming rotation ,translation and scaling. We will refer to coordinates in the first system by x,y, and in the second by u,v. The equation of affine transformation are:

$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} e \\ f \end{pmatrix} \qquad \text{(Eq. 11)}$$

The transformation is uniquely determined by the six parameters a, b, c, d, e and f. Essentially three reference points are needed in both coordinate systems, establishing the transformation parameters. Given these parameters a set of coordinates in one system can be predirected in the other. The interface of transformation software named VIRTUAL STAGE SYSTEM by LabVIEW is shown in Figure 30.

The usage of VIRTUAL STAGE SYSTEM for CIPS software is as follows.

I. Load image on a display area (1) with (3)open button.

II. Set (6)(7)(8)three reference points and target point with cursors.

III. Move the sample stage of SIMS to these references to make relationships and click (4)VALID button to store the X-Y coordinate of the sample stage for each points.

IV. Click (5) Go to button to move the sample stage corresponding to the target.

The Interface of VIRTUAL STAGE SYSTEM for local computer is shown in Figure 31. This software is designed to match two images in the environment without

CIPS. Then, to determine the sample stage position of SIMS, input the stage value into (13) manually.

The usage of this software is as follows.

I. Load images on display area (1) and (2).

II. Set three reference points with cursors

III. Click (3) or (4) run button, (11) and (12) target points start to follow up each other.

Data processing

Because automation software described in this section allows to experiment for hours on end without fatigue, large quantity of experimental data comes to be obtained. Then, batch data processing tool was developed. The interface of correction image generator named N is shown in Figure 32. This program transform (1)raw data to (2)corrected images using (3)parameters generated by 5-polynominal methods described in §2.7. In order to compare these images, an image viewer named MULTI VIEWER was developed. The interface of this program is shown in Figure 33. This program show (2)thumbnails of 9 images in conjunction with (1)working image area and operates slide show the user-established images at certain intervals on (1)working image area to compare each images and calculate isotope ratios of interest region.

Continuous spot analysis

TiTech IMS-1270 lost the ability of scanning method because the detection system was change to multi-collector system. But we consider that continuous spot analysis can perform like scanning method. We tried the method to modify the CAMECA software named scan_param. The scan_param can change the parameters of SIMS instruments continuously. We modified scan_param to scan the parameters to move the position of primary beam two-dimensionally. The interface of modified scan_param is shown in Figure 34. The parameter to move the primary beam to x axial direction is Def4X and y axial direction is Def4Y. Def4X move the beam position about 0.13μm/digit, and Def4Y move the beam position about 0.7-0.8μm /digit. Then it is inputted (2) the steps and delta value with the x-y ratio about 1:5.

3. Results and Discussion

3.1. Conversion factor

The accumulated charge V_{PIX} produced as a result of the interaction of incident particles and pixel electrode through transistors on chip, current-voltage conversion circuit, differential amplification circuit, A/D converter. Finally, it is measured as ADU. Under FDRO operation, the V_{PIX} is set to about the same as reset voltage PIXVRS because the reset transistor M_{RS} works as a switch. The typical value of PIXVRS is 1.5V in high speed readout and 1.0V in high precision read out. The conversion factor between V_{PIX} and ADU can be estimated to change the PIXVRS with the external power supply (KENWOOD PWR18-1.8Q). The readout speed was 4MHz/pixel. The SCAPS was not cooled. Two experimental were performed. In Run 1, the PIXVRS was set to 0V, 0.5V, 1.5V, 2.0V, 2.2V, 2.5V, 2.7V, 3.0V, 3.5V, and 4.0V. And in Run 2, the PIXVRS was set from 1.5V to 2.2V of 0.1V step.

The result of run is shown in Figure 35. The ADU data is average of all pixels except optical black. From 3V to 4V, ADU is about the same value. The silicon substrate is natural electrically at PIXVRS 5V corresponding to gate voltage because the read out transistor M_{RD} is PMOS. ADU begins to go up from about 2.7V to 2.2V gradually. From the character of a semiconductor, depletion layer is formed by the interface of a silicone board and a gate oxide, and this is considered for diffusion current to flow between source and drain. From 0V to 2V, the slope of ADU is almost linear. In the silicone substrate surface, "inversion" takes place near 2V, and this is considered that the conduction electronic concentration in an inversion layer goes up if gate voltage is lowered. This linear region is used for accumulation of an electric charge.

The run2 was performed more about the range of 1.5V-2.2V because typical voltage of pixel electrode in high speed operation of SCAPS is 1.5V. The conversion factor was calculated as 1.65mV per 1ADU from the inclination by the least-squares method of linear region. A pixel capacitance of 14fF as estimated from the layout and process parameters of SCAPS. The elementary electric charge is $1.6e^{-19}$ coulomb. The accumulation electric charge corresponding to 1ADU is estimated as 370 electrons.

3.2. Output characteristics of cooling

Because the output intensity of the SCAPS depends largely on the device temperature. The measurement of cooling characteristics of Hybrid SCAPS system is important for quantum experimentation. However the temperature should be directly measured by thermo couple, it was difficult to attach a sensor to SCAPS. Then the output characteristic of hybrid SCAPS system was estimated to be compared with the conventional SCAPS system already understood with thermo couple.

In the conventional SCAPS system, because MCP was not used, SCAPS could be pressed down to cold finger from a top of device package. Therefore, the SCAPS device was kept constant at low temperature.

The typical output of the conventional SCAPS system that began to cool is shown in Figure 36. The thermal output characteristic of SCAPS can be attributed mainly to dark current and the temperature dependence of the electrical conductivity of semiconductor. The explanation of these characteristics is tried by the following description qualitatively.

The dark current of SCAPS has been discussed (Kunihiro, 2001; Takayanagi, 2003). The dark current of SCAPS is caused by thermal generation current and by gate leakage current in the pixel. Thermal dark current is dominant at temperatures exceeding 230K. Under 230K. the dominant dark current changes to an electron leakage. The dark current was estimated to be 16e^- per pixel when the integration time is 1 hour at maximum.

The electrical conductivity of semiconductor is related to the carrier concentration and the carrier mobility. The carrier mobility is proportional to the average of scattering interval and the scattering frequency can be expressed the effect of the lattice vibration (Bradeen and Shockley, 1950) and the impurity scattering (Conwell and Weisskopf, 1950). At room temperature, the effect of lattice vibration is dominant and the carrier mobility become large, as temperature is lowered. At low temperature, the effect of Rutherford scattering effect of coulomb interaction between the carrier and ionized impurity becomes dominant, and the carrier mobility becomes small again at low temperature from a certain temperature. At room temperature, the carrier concentration is almost equal to donor (acceptor) concentration because donors (acceptors) ionize all mostly. At low temperature, the carrier concentration decreases because valence electrons that are thermal excitation to conductive band decreases. In order to measure the carrier concentration and the carrier mobility, the Hall effect is often used. However, it is outside the scope of this paper.

The temperature of SCAPS before LN2 pouring was equal to the room temperature (1). Liquid nitrogen was started to pour into the Dewar (2). The SCAPS device was star to cooling (3). In the high temperature like room temperature, the dark current which was exhausted the charge of capacitor is caused by thermal generation current. Because the thermal dark current decreases exponentially with cooling of SCAPS, the output voltage of SCAPS turns up. This slope is mainly related to the rate of reduction of thermal dark current. Two kinds of states can be considered at (4). }Thermal dark current was almost lost below 230K. Or the effect of reduction f thermal dark current becomes less than the effect of decline in the rate of electric conductivity is dominant. Heat generated by the drive of SCAPS and cooling by LN2 come to equilibrium at (6). In the conventional SCAS, the temperature of SCAPS measuring by thermo couple is 100K in the state of equilibrium.

In the Hybrid SCAPS system, because the MCP moving unit moves on SCAPS, the SCAPS could not be pressed down to cold finger from a top of device package. Then, in order to keep SCAPS device constant at low temperature, a certain gimmick was needed. Six types of cooling assemblies were manufactured by way of try. Figure 37 shows photographs of assemblies. Improvements were added from (a) to (f). The measurement conditions were as follows. Liquid nitrogen was poured into Dewar and output data of SCAPS was recorded in the LDRO operation by high-precision readout system. In this experiment, Dr. Nagashima could offer many great ideas and advanced manufacture techniques.

In Figure 37-(a), dotite is applied on cold finger of Cu and it is made to pate up with cold finger and SCAPS. The connection between the pin of SCAPS and feedthrough used the socket pins (mac8). The order of assembly was SCAPS – PD51 – PD9 – PD11 – Feedthrough. The substrates made of Teflon were inserted between PD9 and PD11 in order to make easy to assemble and prevent to contact each pins. Figure 38-(a) shows the output characteristic under cooling with type (a). An output higher than the conventional SCAPS means not been cooled to 100K. As possible cause, adhesion with

SCAPS and cold finger was inadequate. Although Cu cold finger and stainless steel of chamber were contracted by cooling, SCAPS is fixed with the socket pin. Then the adhesive force of dotite was defeated by the separating power of thermal contraction.

In Figure 37-(b), the wire connected SCAPS and feedthrough instead of the pin so that SCAPS might also move maintaining to bond, with contraction of Cu. The result is shown in Figure 38-(b). The output became low to near the output of the conventional system. The slope of (2) is higher than conventional system and shorter time was taken before the output is stabilized. It is thought that dotite raised thermal conductivity. However, the output was going up in measurement of another day. Moreover, when MCP was moved, SCAPS also moved in connection with the motion. As a result of changing a socket pin into a wire, it can move now with Cu which carries out heat contraction. On the other hand, SCAPS moves by friction with MCP moving unit and the SCAPS package surface, and it is thought that the adhesive strength of dotite declined.

In Figure 37-(c), the innermost pins of SCAPS are bent to strap the SCAPS into the Cu cold finger. This gave to prevent the perpendicular direction motion of ion trajectory axis by the movement of MCP. Moreover, adhesion with Cu is strengthened by dotite being mostly attached between the bent pins. The result is shown in Figure 38-(c). The output is lower than (b) and less also than the conventional SCAPS ((c)-1). However, like (b), the output was going up in measurement of another day. As possible cause, adhesion state of dotite was also changing in this case. In order to connect wires to SCAPS, advanced technique is required, and it is very difficult to carry out without damaging the pin of a SCAPS device.

In Figure 37-(d), the socket pin PD91 was used instead of the wire of (c). The result is shown in Figure 38-(d). The output was lowest. However, like (b) and (c), the output was going up in measurement of another day by the same token.

In Figure 37-(e), the leaf spring was used to contact SCAPS and Cu instead of dotite. By this method, even if Cu contracts, Cu and SCAPS are contacted by spring support. The electrode of EM made from Cu-Be was processed and used as the leaf spring. The leaf spring was fixed on Cu cold finger by dotite. The result is shown in Figure 38-(e). This structure didnot work. The fact that the spring lost its effect or that the spring was not fixable to Cu is cited as this cause.

In Figure 36-(e), Crimping terminals were soldered with the pin of SCAPS, and it is fixing with the fixing brackets of Cu with the screw. Dotite did not used. The detail of fixing brackets is described in §2.4.4. The result is shown in Figure 38-(f). By this method, whenever it measured, an output did not change. However, the output became unstable suddenly because of the absence of strength of crimping terminals. The problem of this unit, the crimping terminals was stressed by rotation momentum. Therefore, strengthened crimp terminal with solder was attached. More improvements were still required.

The examination of in this paper was performed under the condition of Figure 37-(a)

3.3. Single ion

The accumulation signal of a pixel in one frame decreases with increasing the read-out speed. The sensitivity of high-speed readout system is important property to adjust instruments for minute amount of isotopes in a sample such as ^{13}C, ^{17}O. Then, the sensitivity was measured by single ion counting method. This method means the ability of detecting incidence ion one by one.

The experimental conditions are as follows. MCP was irradiated by ^{18}O ions sputtered from SPU. Amplified signals as electrons were acquired by SCAPS at 9.35 frame/sec with LDRO readout operation. The total counts of ^{18}O ion was 1000 cps (count / second) measured by EM. SCAPS was cooled by LN2. The potential of back electrode of MCP moving unit was fixed at +16V. The potential of front electrode was set to –1100V, -1050V, -1000V, -950V, and -900V. Considering 58% of the open area ratio of MCP, about 62 ions will be existed in an image.

In order to discriminate the signal of incident ions from back ground noise, two kinds of methods were adopted. One was the method of manual discrimination and the another method was that of auto-detecting using image processing by computer. Ideally, the incident ions should be counted over-and-short account. But the counting algorism was not perfect. It is better to fail to count rather than it counts a noise in order to determine the lower limits of counting.

The resolution of input image was singed integer 12bit, and the size was 576x608 pixels. The procedure of this method was below. First, FPN correction was performed by subtracting a dark frame from input image, and the image of float 32bit was obtained. The FPN corrected image is shown Figure 39-(1). The signal of incidence ions was expressed by black color (small pixel value) in the image after compensation. The corrected images were used in subsequent process.

The following assumptions were set to discriminate the signal of incidence ions.

I. The irradiation area of ions is inside of the detection area of SCAPS.

II. Two or more ions were not irradiated into a single channel of MCP simultaneously.

III. Because the channels of MCP has circled figure, the signal detected by SCAPS close to a circle.

IV. Since there is a distance between the output side of MCP and the detection side of SCAPS, the detected signal forms the halo spread within a certain area.

Procedure of Image processing was shown in Figure 39-(2) to 39-(8). The software library of LabVIEW called IMAQ Vision (Naitonal instruments) was used for image processing.

Firstly, in order to reduce the noise of images and make easy to detect the peak of the pixel value which constitutes the signal of incident ions, smoothing method using Gaussian kernel (1.5 pixels of standard deviation) was executed. Then image of Figure 39-(2) was obtained. Convolution using Laplacian kernel was applied to this image (Figure 39-(2)) in order to high light the signals. Then Figure 39-(3) was obtained. If the central coefficient is greater than the sum of the outer coefficients ($x > 2(a+b+c+d)$), the Laplacian filter extracts the pixels where significant variations of light intensity are found and superimposes them over the source image. Two kinds of Laplacian kernels are adopted. One is 5x5 kernel consisted the center value 30, and the others was –1. Another is 5x5 kernel consisted the center value 60 and others are –1.

After that, a threshold was determined in order to binarize the image. The region considered that incident ion probably does not exist was set as ROI (region of interest) corresponding to the square region of Figure 40, and (average value) – 3 × (standard deviation) was used as a threshold. This calculation was expressed by subtracting because the signal was expressed with the small pixel value. using this threshold.

In order to remove the peak caused by the noise, the Auto-Median filter expressed by the following formula was applied. It generates simpler particles that have fewer details.

Auto-median(I)=min(DEEDDE(I), EDDEED(I))

Where I is the source image, E is an erosion, D is an dilation. Erosion reduces the brightness of pixels that are surrounded by neighbors with a lower intensity. Dilation increases the brightness of each pixel that is surrounded by neighbors with a higher intensity. A noise was lost by applying the low pass filter of further 3x3.

Then, Circular analysis and particle analysis using Danielson coefficient map as an analyzing method were adopted to estimate the numbers of particles. An original and the analyzed image were shown in Figure 39-(a) and 39-(b).

The number of the ion distinguished are shown in Figure 41. However, the number of the distinguished ion at -1050V is nearly equal to the number of the distinguished ion at -1100V. The average value is close to the number of ion which was estimated to detect. This means that the detection efficiency of MCP is mostly dependent only on the rate of a opening. Furthermore, the all signals of the incident ion outputted from MCP can be detected with SCAPS.

There is much 3-4 number of the ion at -1050V from -1100V. One possible reason was the counting loss caused by the counting algorism. The signal of incident ions has overlapped with the signal of the nearby channel. In the case of squared area in Figure 40, the threshold is gradually raised from the noise level. The overlap was considerable by the difference among 50V because of the gain of MCP increases exponentially. The own algorithm should be developed such as Nittler's particle-definition algorithm or "clumpfind" (Williams) used in the field of radio astronomy.

Another possible reason of the difference, there were undeniable possibility of fluctuation of primary ions because the total amount of ions were measured by EM between an intervals of measurements in each voltage value. If the total amount of ions were changed 50-60cps, the difference of -1100V and -1050V will be explained by fluctuation of primary ions. This problem may be solved by the multi-collector system of SIMS. The multi-collector system can monitor the other isotope simultaneously during measurement.

In this measurement, it is safe to say that SCAPS can detect the all signal to incident ions. And hybrid SCAPS system can detect single ion roughly.

3.4. High precision isotopic ratio ion imaging

Schematic block diagram of measurement procedure to obtain high precision isotopic ratio images by isotope microscope using hybrid ion imaging system is shown in Figure 42.

The basic procedures are described to follow the figure.

I. Set up SIMS instruments and SCAPS system in high-speed readout mode.

II. Primary ion beam and secondary ion optics are tuned with Cu-Al grid or Si wafer with which the micron-size pattern was formed and an isotope image of these test samples is acquired to determine the spatial resolution in high precision readout mode.

III. After replacing the test sample with the actual sample, the sample stage is moved to the measuring region. The transformation of coordinate software described in §2.6.4 is used when it is difficult to determine the position.

IV. Analytical conditions are defined such as the isotope, the number of measuring. The number of measuring frames is determined by the estimation of statistical error required the measurement from the natural abundance of isotopes.

V. If the sample was coated for charge up proof, the coat is peeled off by bombarding of primary beam for a while. This operation called pre-sputter. Final adjustment of secondary ion optics and mass calibration are executed during the pre-sputter. Because just a little wrong adjustment make the fatal narrow spatial resolution for microanalysis, this process is most important.

VI. Select isotope from the list of isotope to be calibrated the mass and the magnetic power of magnetic analyzer (Fig. 1 (14)).

VII. An isotope image is measured following the procedure of §2.6.3 in high precision readout mode. The SCAPS device was cooled by LN2 at 77K.

VIII. If there are additional isotopes to measure in the same region, back to (6), else go to (9). The measurement of this region has been finished.

IX. If there are additional regions to measure, back to (3), else go to (10). The experiment has been finished. Automation software described in §2.6.4 are listed (4)analytical conditions of each isotopes and run the processes from (6) to (8) over again sequentially.

X. The flame data are processed by several correction methods with a computer.

The flow of data processing is linearity correction, reset frame collection, pixel binning, and alignment of ion images. Linearity correction method was proposed by Nagashima. The linearity of output of SUSHI (latest SCAPS) is better than the conventional SCAPS. Then following 5-order polynomial equation is adopt instead of (Eq. 7).

$$N_i = N_R\left(a_0 + a_1 V_{OUT_i} + a_2 V_{OUT_i} + a_3 V_{OUT_i} + a_4 V_{OUT_i} + a_5 V_{OUT_i}\right) \qquad \text{(Eq. 12)}$$

This method is acceptable practically for SUSHI because of the good output characteristics. These parameters are determined to integrate incident ions such as $^{30}Si^{+}$ with the individual pixels of SCAPS and simultaneously detect the total number of secondary ions coupled the incident ions of SCAPS such as $^{28}Si^{+}$ by dimensionless detector like FC. This situation realized by an unique technique to use the flight tube in the magnetic sector to resemble FC using IMS-3f (Nagashima et al.,2001). In isotope microscope using TiTech multi-collector IMS-1270, a FC detector of multi-collector system is used to detect the total number of secondary ions. The seven detectors of the multi-collector system were lined on the mass dispersion plane placed between magnetic sector (14) and exit slit (15)in Fig. 1 in IMS-1270.

After the linearity correction, reset frame correction (Kunihiro et al., 2002) is applied to cancel the fixed pattern noise to divide the isotope image by reset frame called dark frame in this thesis. In order to measure the distribution of isotopic ratio of sample surface, the isotope images from which acquisition time is different are standardized by the acquisition time equal to the number of frames.

In order to increase the signal-to-noise ratio, pixel-binning technique (Kunihiro 2001) is applied to ion images. Increasing the precision by this technique, decreasing the spatial resolution. However, one pixel corresponds to $0.17\mu m \times 0.17\mu m$ on the sample surface in the typical condition using the conventional SCAPS system with high-mass resolution (Yurimoto et al., 2003). Because the spatial resolution is dominated by the ion optics of SIMS instruments, this binning technique is less of an obstacle to the special resolution such as 7×7 pixels binning. The isotopic ratio image can be obtained by division process.

Projected positions of each isotope image are not exactly equivalent on the SCAPS pixel and shifted horizontally or vertically about half of one pixel. When this effect occurs, the isotopic ratio image shows sets of peak and dale region. In order to decrease this effect, shift the raw data directions to negate these distributions first, and second bind the shifted isotope image, and finally divide two images to make isotopic ratio image.

4. Summary

1. A hybrid ion imaging system using SCAPS detector has been developed for secondary ion detector. This system is used for high-precision readout and high-speed readout.
2. For the high-speed readout mode, the conversion factor of the accumulated charge is 1.65mV/ADU. This value was estimated to 370 electrons in a pixel.
3. The cooling unit is newly designed. The cooling ability of new unit is better than old system.
4. The hybrid ion imaging system performs detection of single ion at the high-speed readout (4MHz/pixel), high-precision measurement with low noise (correspond to 3 ions), and high dynamic range (87dB) by the same device.

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6. References

Badeen and Shockley (1950), Deformation Ptentials and Mobilities in Non-Plar Crystals, *Phys. Rev* vol1. 80, pp72

Conwell and Weisskopf (1950), Theory of Impurity Scattering in Semionductors, *Phys. Rev* vol1. 77, pp388

Hunter J. L., Linton R. W. and Griffis D. P. (1991) High dynamic range quantitative image depth profiling of boron in patterned silicon dioxide on silicon. *J. Vacuum Sci. Technol. A* **9(3)**, 1622.

Hoppe P., Strebel R., Eberhard P., Amari S., and Lewis R. S. (2000) Isotopic properties of silicon carbide X grains from the Murchison meteorite in the size range 0.5-1.5 ｵm.*Meteroritics Planet. Sci.* **35**, 1157-1176.

Johnson (1925), The Schottky effect in low frequency circuits, Physical Review, 26:71-85.

Kunihiro T. (2001) Development and noise analysis of stacked CMOS-type active pixel sensor for charged particles. *PhD Thesis*.

Kunihiro T., Nagashima K., Takayanagi I., Nakamura J., Kosaka K. and Yurimoto H. (2001a) Noise characteristics of stacked CMOS active pixel sensor for charged particles. *Nucl. Instr. and Meth. A*.

Matsumoto K., Yurimoto H., Kosaka K., Miyata K., Nakamura T. and Sueno S. (1993) A novel ion imager for secondary ion mass spectrometry. *IEEE Trans. Electro. Devices* **40**, 82.

Nagashima K., Kunihiro T., Takayanagi T., Hirata T. and Yurimoto H. (1997) Characteristics of output signal of Amplified MOS Imager. In *Proc. International Symposium on Atomic Level Characterizations for New Materials and Devises '97*, 339-342.

Nagashima K., Kunihiro T., Takayanagi I., Nakamura J., Kosaka K. and Yurimoto H. (2000) Application of active pixel sensor for charged particles to mass spectrometry. *ITE Technical Report (in Japanese)* **24(3)**, 13-18.

Nagashima K. (2001) Development of stacked CMOS active pixel sensor (SCAPS) for two-dimensional isotope analysis - Restoration method from nonlinear output of SCAPS –. *PhD Thesis in Tokyo Institute of Technology*

Nagashima K, Kunihiro T, Takayanagi I, Nakamura J, Kosaka K, Yurimoto H. (2001)

Output characteristics of stacked CMOS-type active pixel sensor for charged particles. *Surf. interface anal.*

Odem R. W., Furman B. K., Evans Jr C. A., Bryson C. E., Petersen W. A. , Kelly M. A.,Wayne D. H. (1983) Quantitative image acquisition system for ion microscopybased on the resistive anode encoder. *Anal. Chem.* **55,** 574-578

Sakamoto. (2001), Development of ion imaging system with Stacked-CMOS Active pixel Sensor, Graduation thesis *in japanese*

Takayanagi I., Nakamura J., Yurimoto H., Kunihiro T., Nagashima K., Kosaka K. (1999b) CMOS image sensor for charge particle detection. *Technical Report of IEICE (in Japanese).* **99(374)**, 7-12

Takayanagi I., Nakamura J., Yurimoto H., Fossum E.R., Kunihiro T., Nagashima K. (2003) Dark Current Reduction in Stacked-Type CMOS-APS for Charged Particle Imaging. *IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 50, NO. 1, JANUARY 2003*

Wiza, Joseph Ladislas. (1979). Microchannel Plate Detectors. *Nuc. Instr. Meth.*, **162**, 587.

Yurimoto H., Matsumoto K. (1996) Slid-state imager for charged particles. *Bunseki Kagaku (in Japanese).* **45**, 493-500

Yurimoto H., Matsumoto K., Kim K., Kitajima H., Kosaka K., Hirata T. (1997) Development of solid-state two-dimensional ion imaging device and new computer control system for SIMS. In *Secondary Ion Mass Spectrometry SIMS X*, Benninghoven A., Hagenhoff B., Werner H. W. (eds). John Wiley & Sons: Chichester, 987-990

Yurimoto H., Nagashima K, Kunihiro T. (2003) High precision isotope micro-imaging of materilas. *Applied Surface Science 203-204 (2003) 793-79*

	High precision	High speed
VLS	+10V	+10V
DSCH	+4V	+5V
SRXH	+3V	+5V
SRXL	+0.5V	+0.5V
VBP	+3.8V	+5V
PIXVRS	+1.0V	+1.5V
PIXVD	+1.5V	+2V

Table. 1: The values of voltage supply for SCAPS. The leftmost column shows as follows; VLS : Shield electrode voltage, DSCH : Pre-charge bios voltage for colum signal line, SRXH : High level voltage of pixel reset pulse RS, SRXL : Low level voltage of pixel reset pulse RS, VBP : Bios voltage for analog output buffer, PIXVRS : Pixel reset voltage ,PIXVD : Pixel VD.

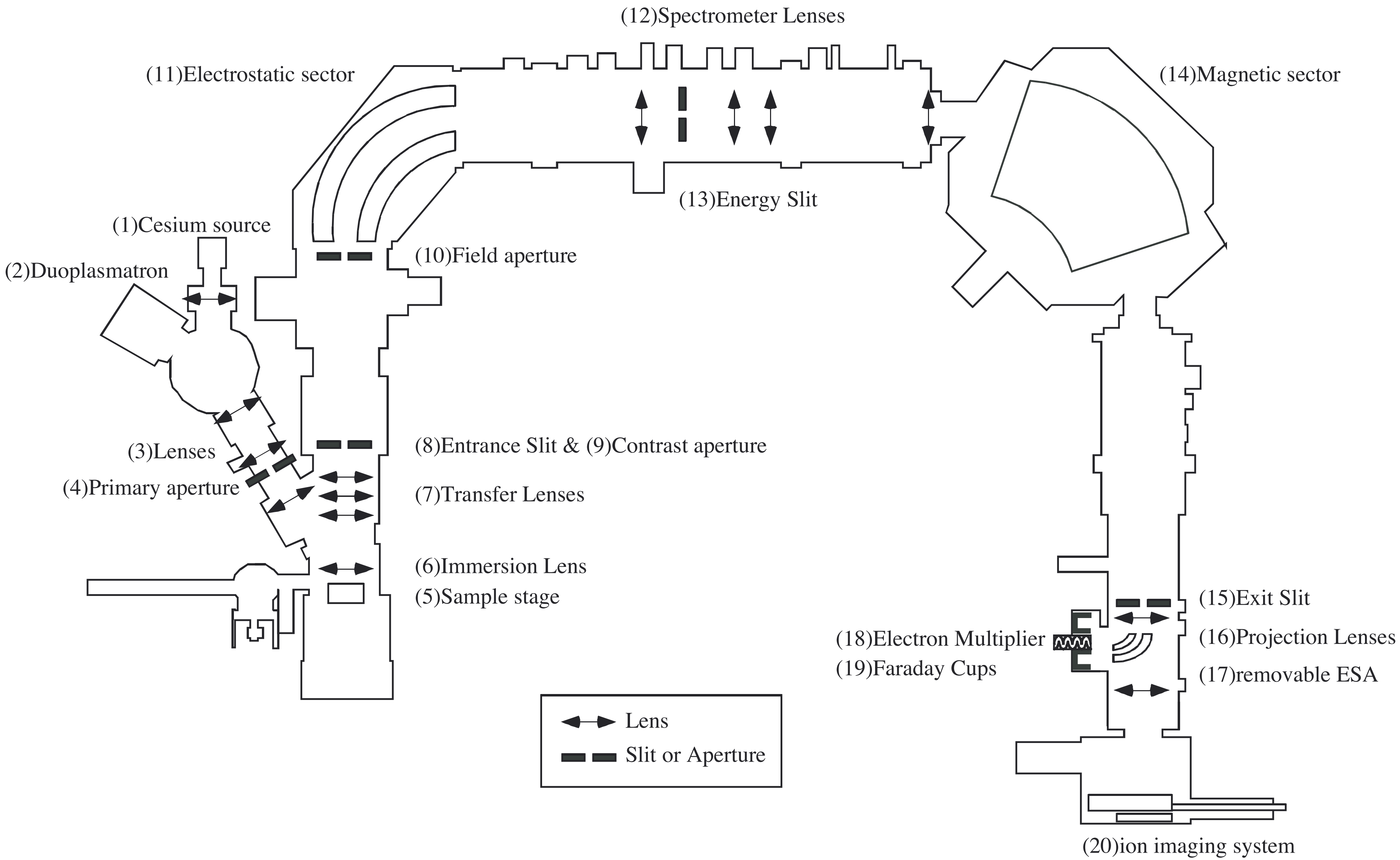


Figure 1: Schematic diagram of the secondary ion-optical system of the CAMECA IMS1270 ion microanalyzer with the hybrid ion imaging system.

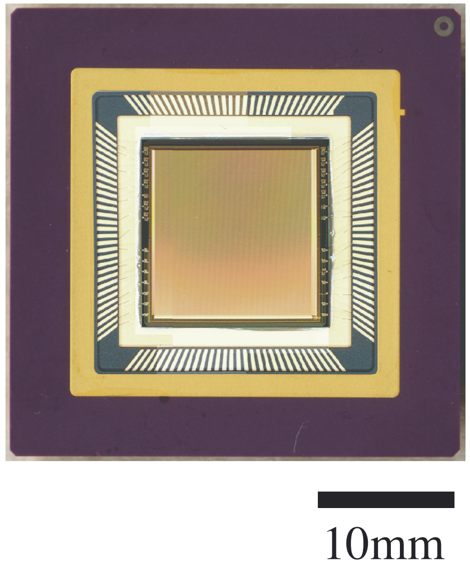


Figure 2: Appearance of SCAPS device assembled in a 120pin PGA package.

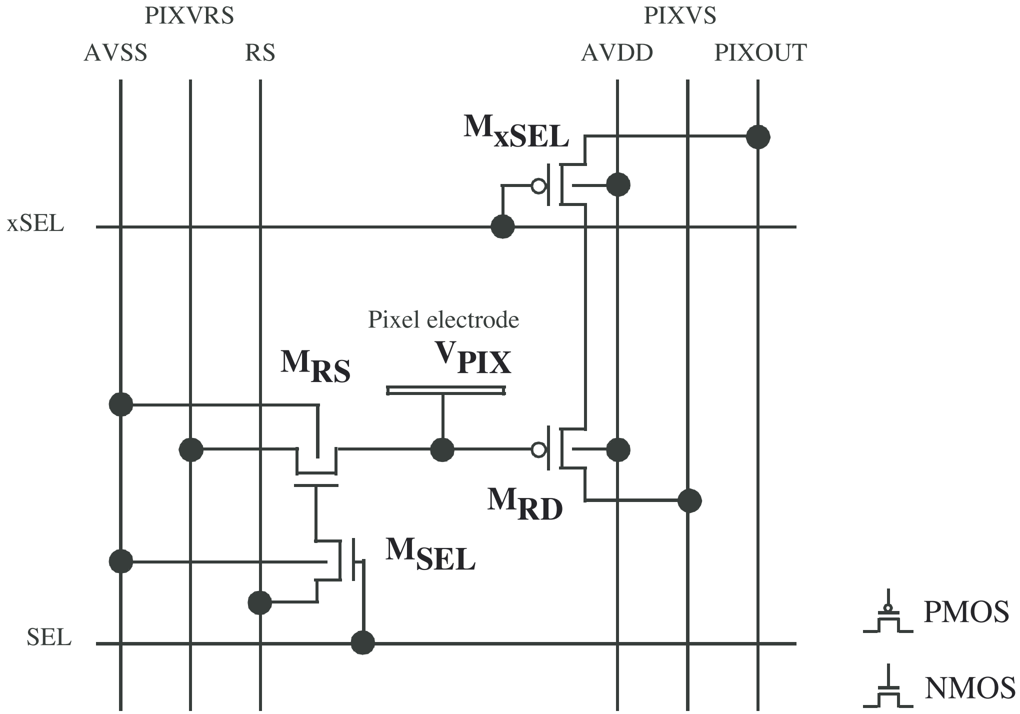


Figure 3: Schematic circuit of a pixel. V_{PIX} is amplified at M_{RD} and readout through M_{xSEL}. M_{RS} and M_{SEL} are reset switches.

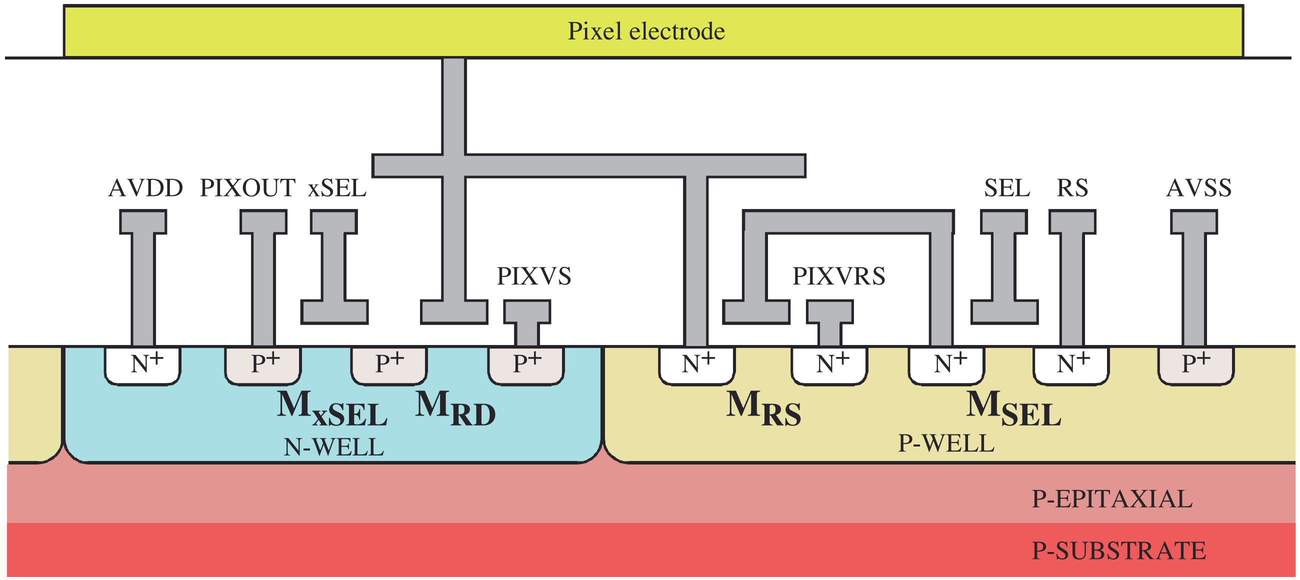
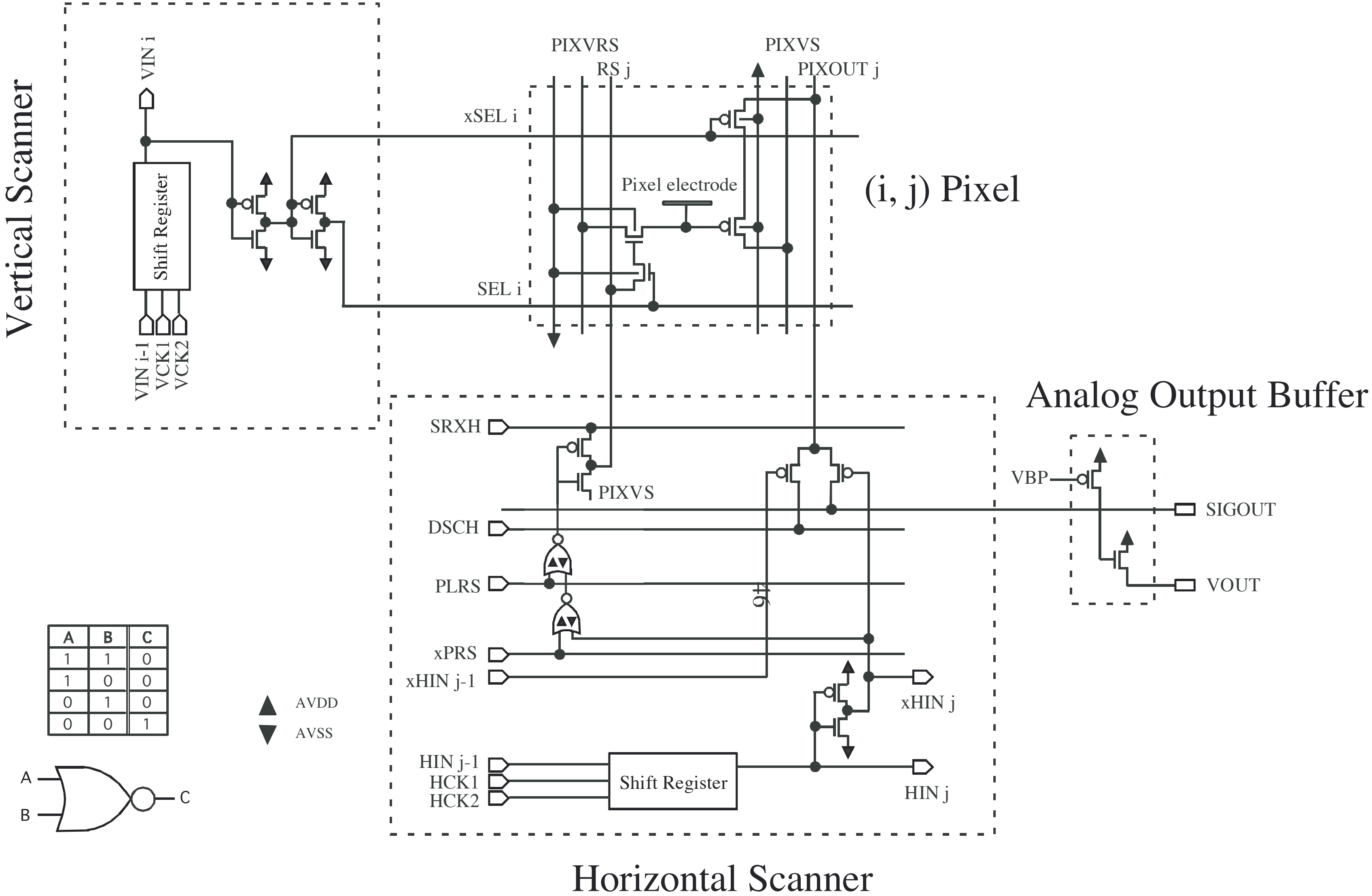


Figure 4: Schematic cross-sectional view of a pixel structure.



A	B	C
1	1	0
1	0	0
0	1	0
0	0	1

Figure 5: Circuit configuration of SCAPS pixel array. SCAPS consists of pixels and driving circuit. Pixels are addressed by a vertical scanner and a horizontal scanner in the X-Y addressing scheme. SCPAS has two paths of signal output. Analog output buffer is used in V_{OUT} mode with VBP 3.8V. SIG_{OUT} mode do not use analog output buffer with VBP +5.0V.

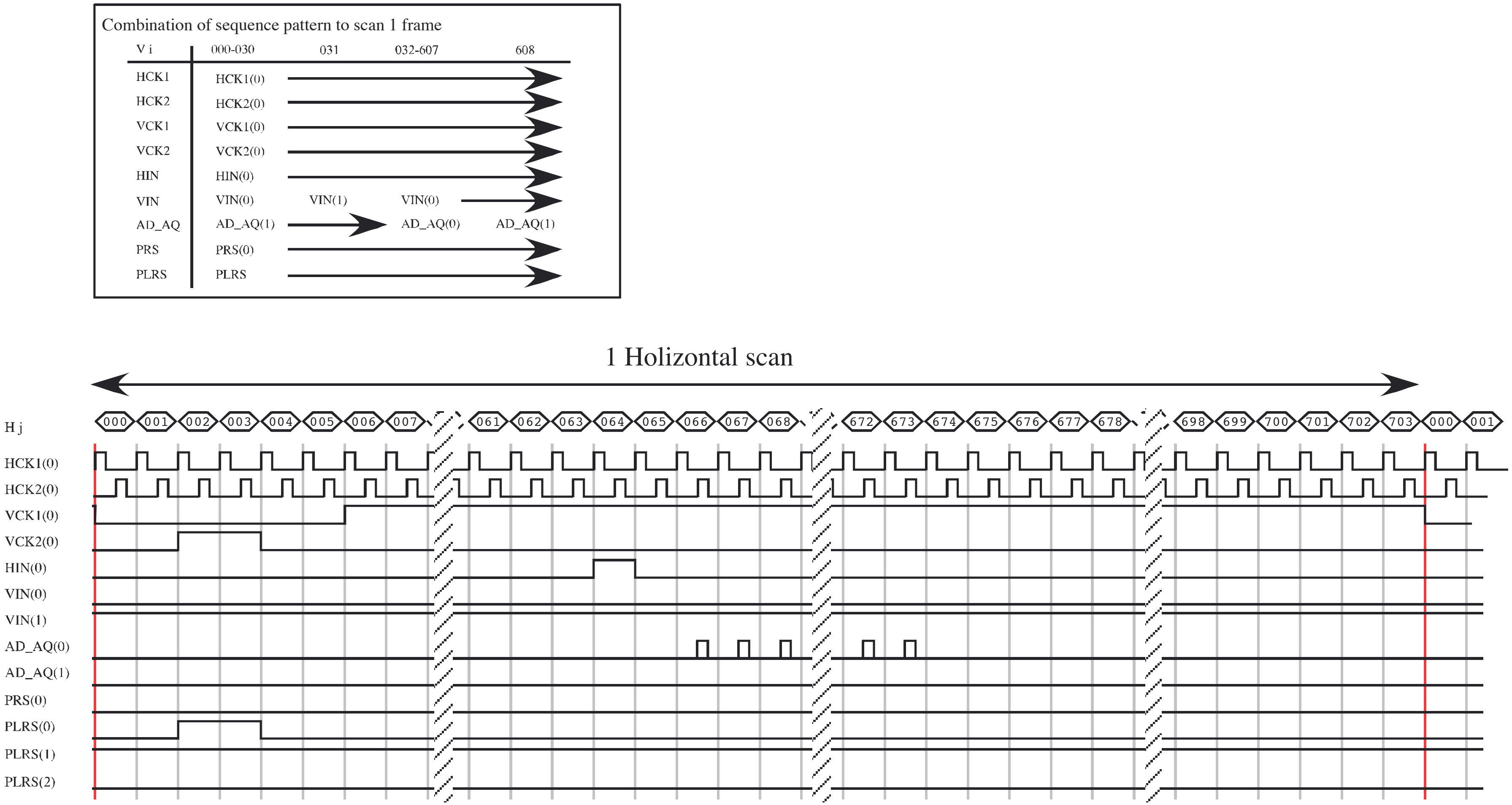


Figure 6: Basic pulse timing to drive the SCAPS. HCK1, HCK2, HIN, VCK1, VCK2, VIN are input pulse to drive horizontal and vertical scanner. AD_AQ is the timing pulse of A/D conversion. VIN(0) is changed to VIN(1) at the end of vertical blanking period only. PLRS is the pixel reset pulse of the selected whole row. PLRS(0), PLRS(1), PLRS(2) are used in LDRO, FDRO, NDRO reset mode respectively.

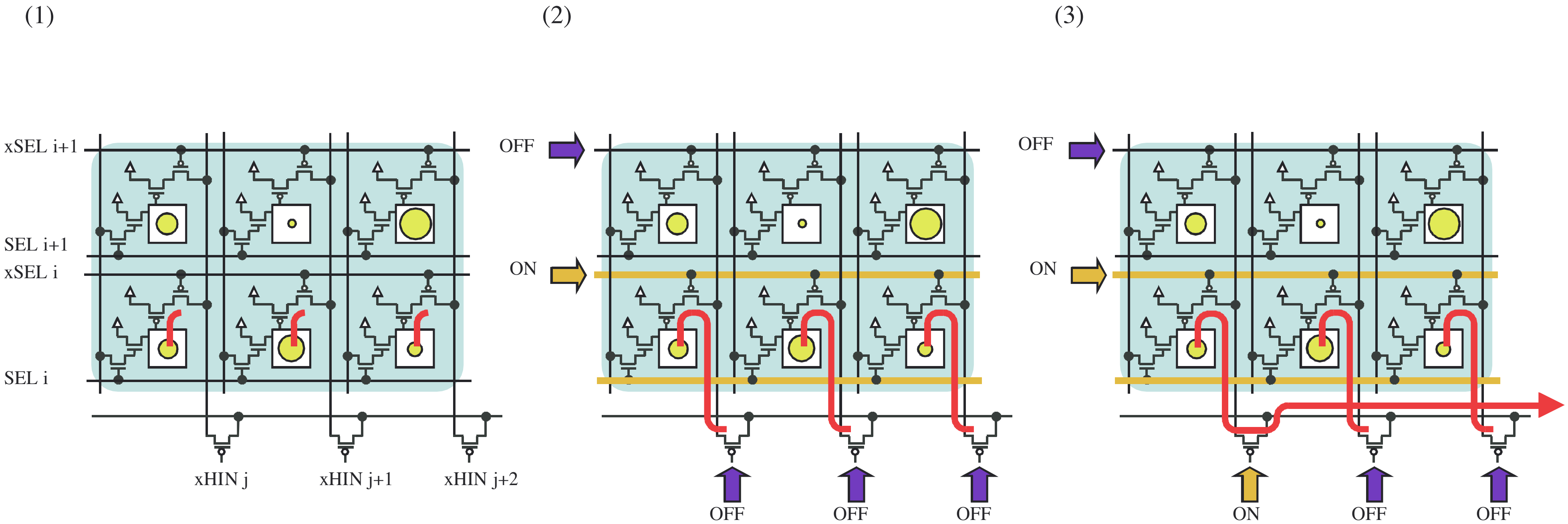


Figure 7: Schematic drawing of readout operation. (1) The state which the electric charge is accumulating. i and j are the address of pixel. (2) The row selection switches are turned ON by the selection pulse SELi and xSELi. All the signals of this line are outputted to each signal line. (3)When the column selection switch $M_{PIXOUTj}$ is turned ON. The signal of a (i, j) pixel is outputted.

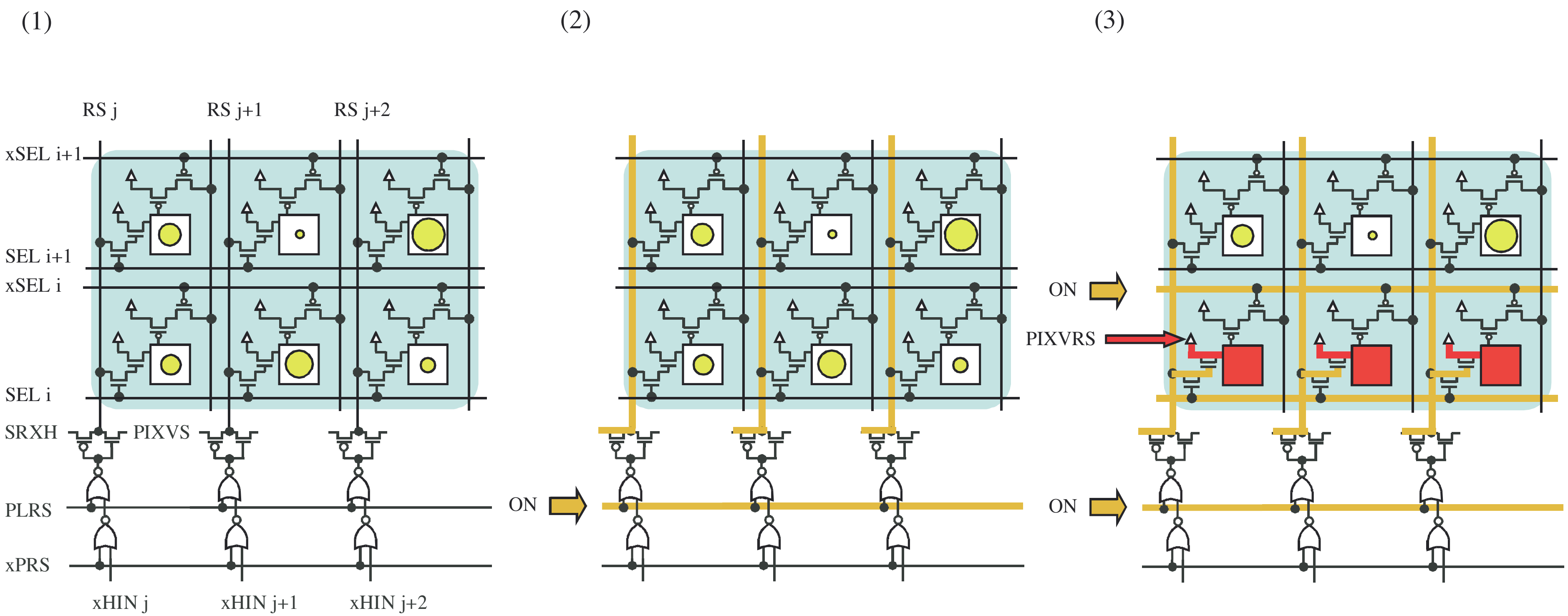


Figure 8: Schematic drawing of Destructive Readout Operation (DRO). (1) The electric charge is accumulating. i and j are the address of pixel. (2) When the line reset pule PLRS is high, all RS lines are set to high voltage SRXH. (3)When the selection pulse SELi and xSELi. The pixel voltages of all this row line are set to the voltage PIXVRS. In Full time DRO (FDRO), PLRS is always high, pixels of each row lines are set the voltage to the reset voltage PIXVRS during the row line are selectecd. In Line DRO (LDRO), PLRS is high during blanking time, pixels of each row lines are set the voltage to the reset voltage PIXVRS during the blanking time typically two pixel time.

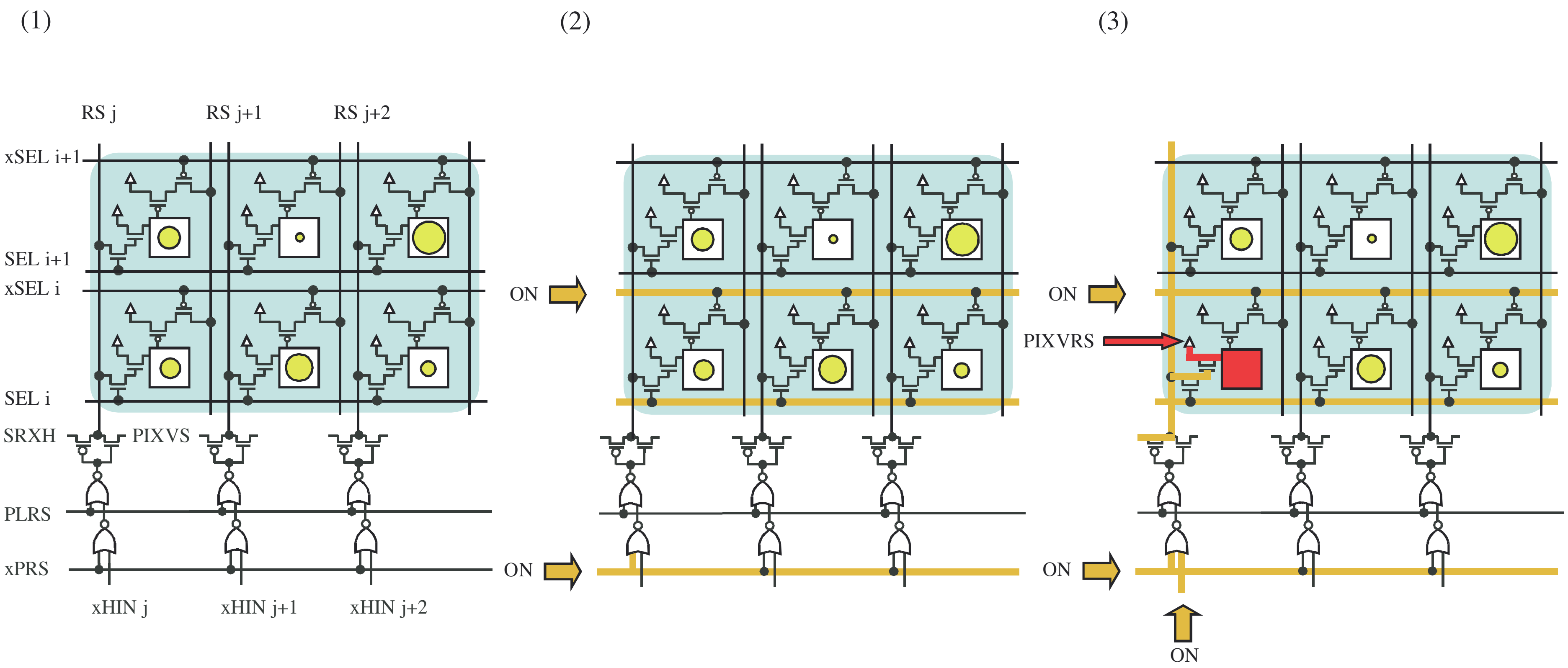


Figure 9: Schematic drawing of individual pixel reset operation (INDIV). (1) The electric charge is accumulating. i and j are the address of pixel. (2) The selection pulse SELi and xSELi and the reset pule PRS are turned ON. (3)When the column select switch xHINj turned ON, RSj is set to high voltage SRXH and the selected pixel is set to the voltage PIXVRS.

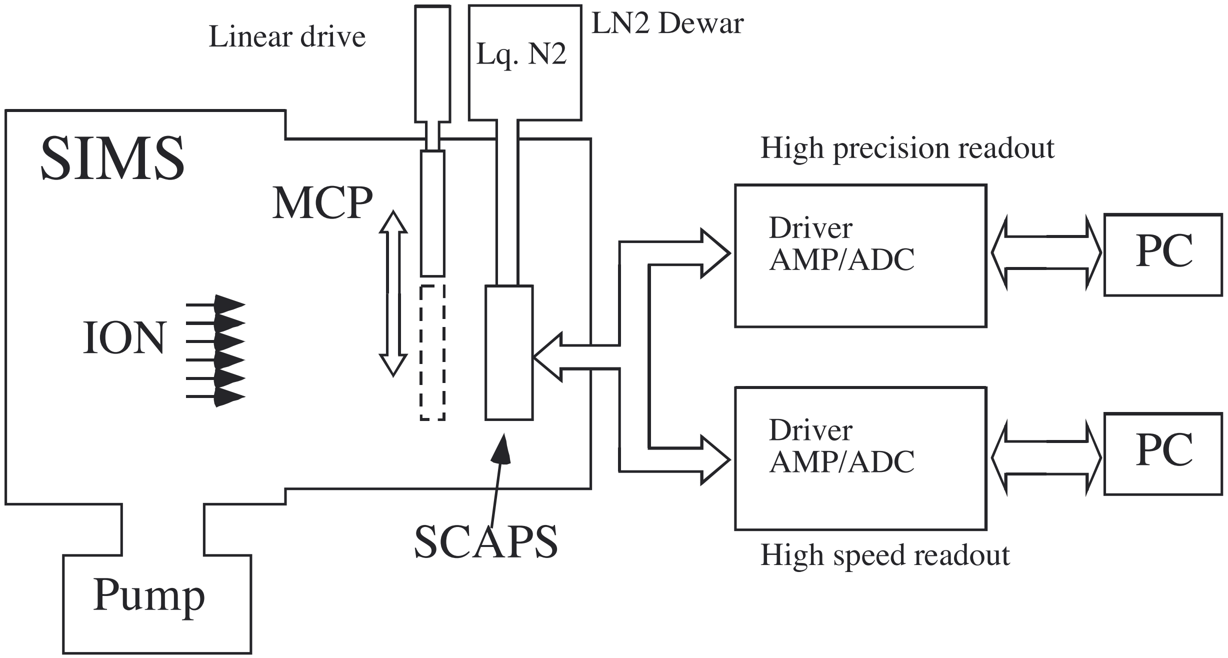
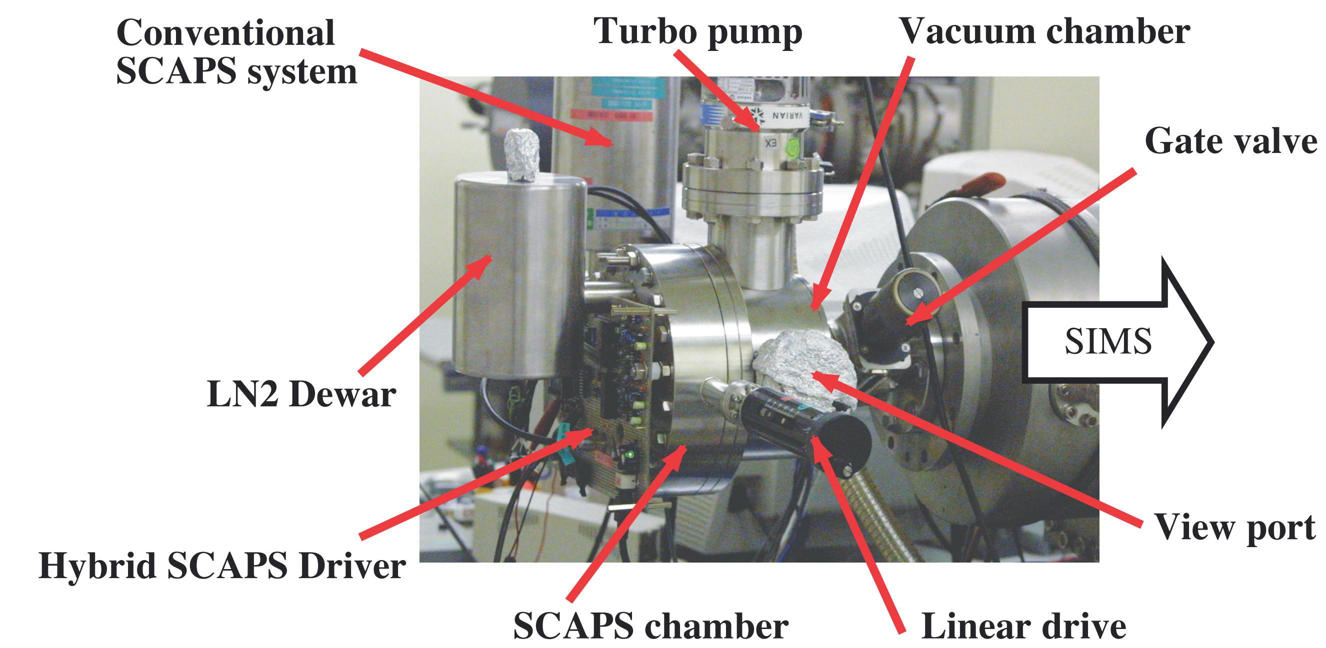


Figure 10: Schematic block diagram of the hybrid ion imaging system. The SCAPS is installed in a projection-type SIMS. MCP just before the SCAPS is removable.

(a) Appearance of Hybrid SCAPS system



(b) Drawing of SCAPS chamber

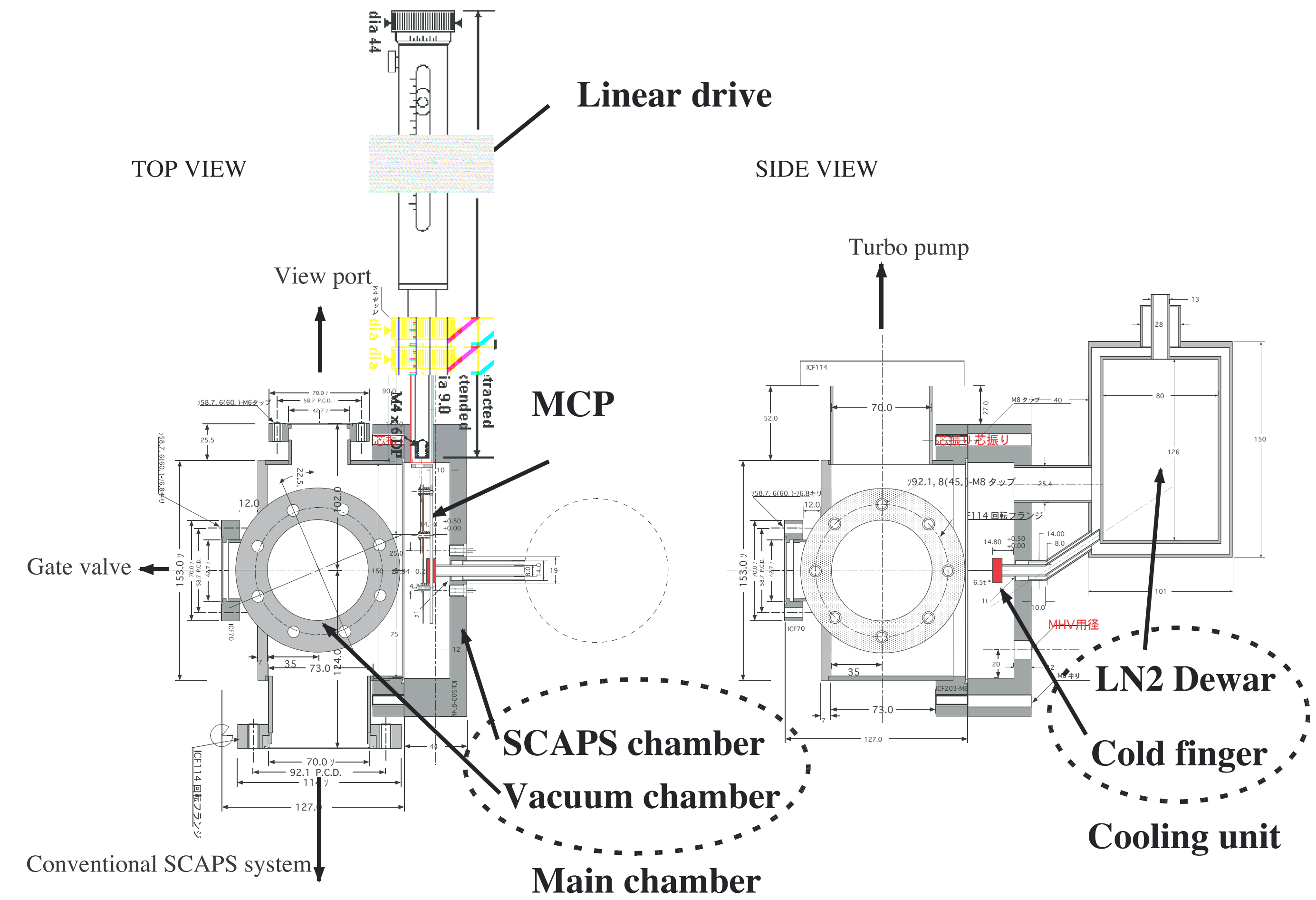


Figure 11: (a)Appearance of Hybrid SCAPS system and

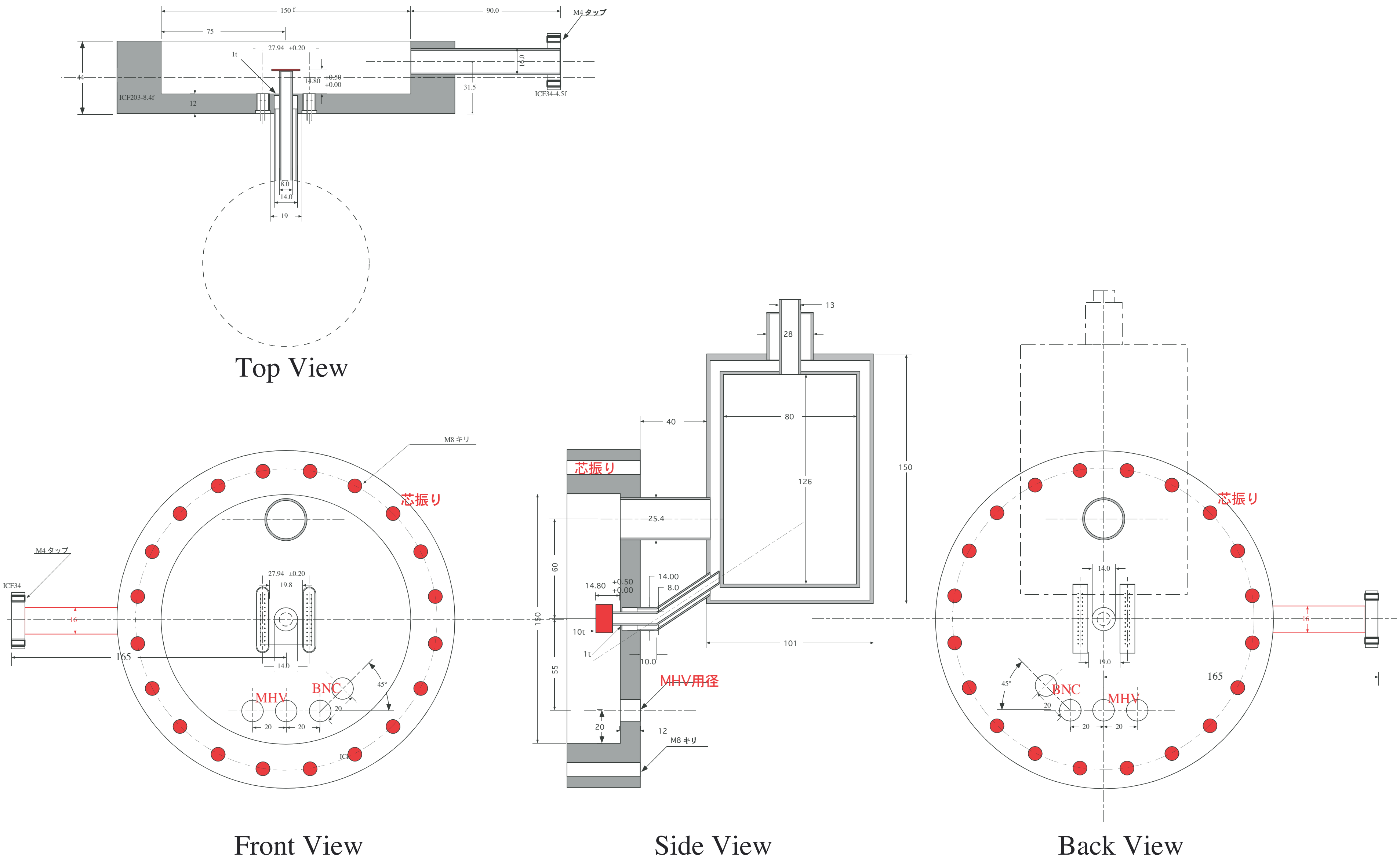


Figure 12: Drawing of SCAPS chamber.

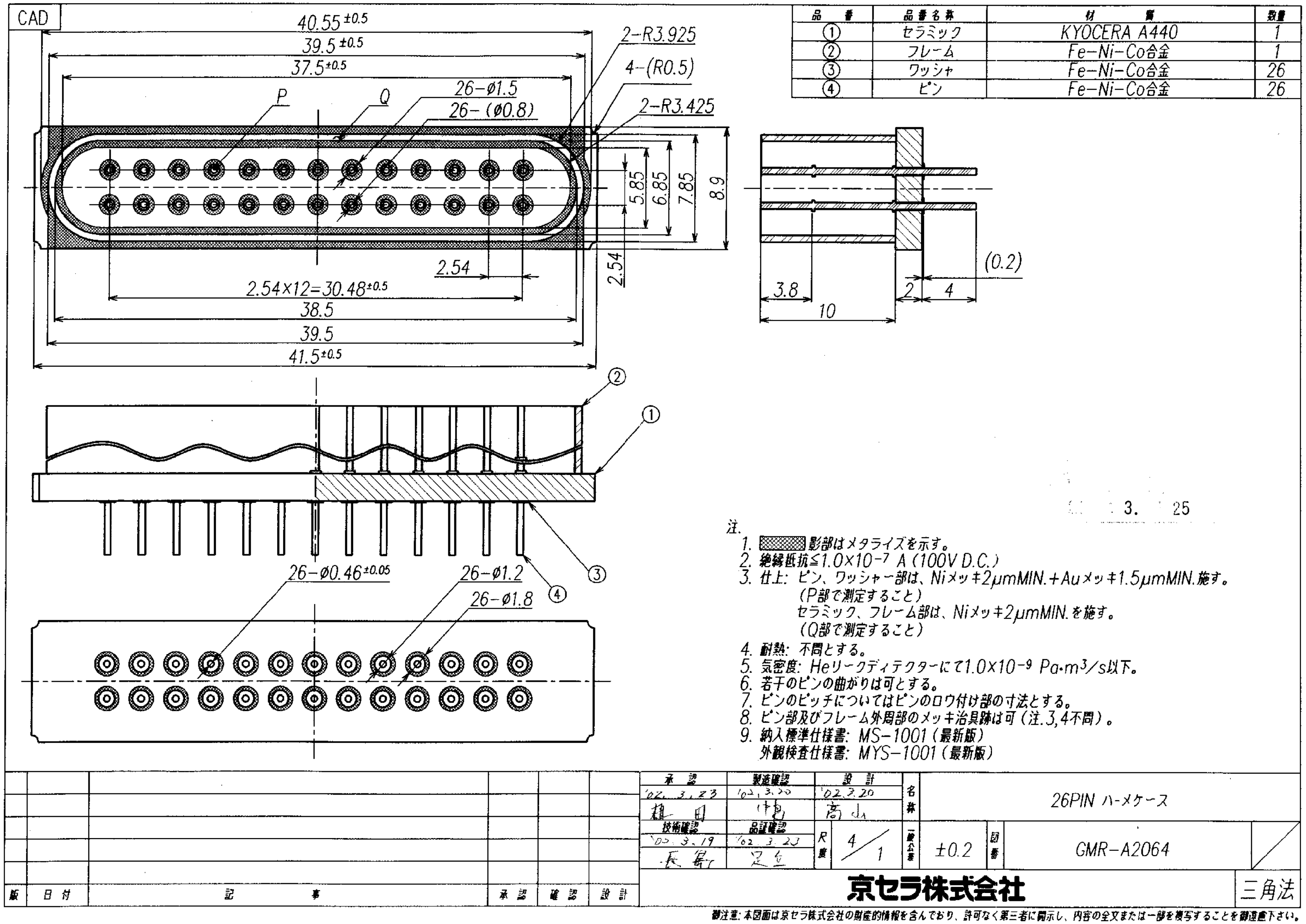


Figure 13: The drawing of feed through.

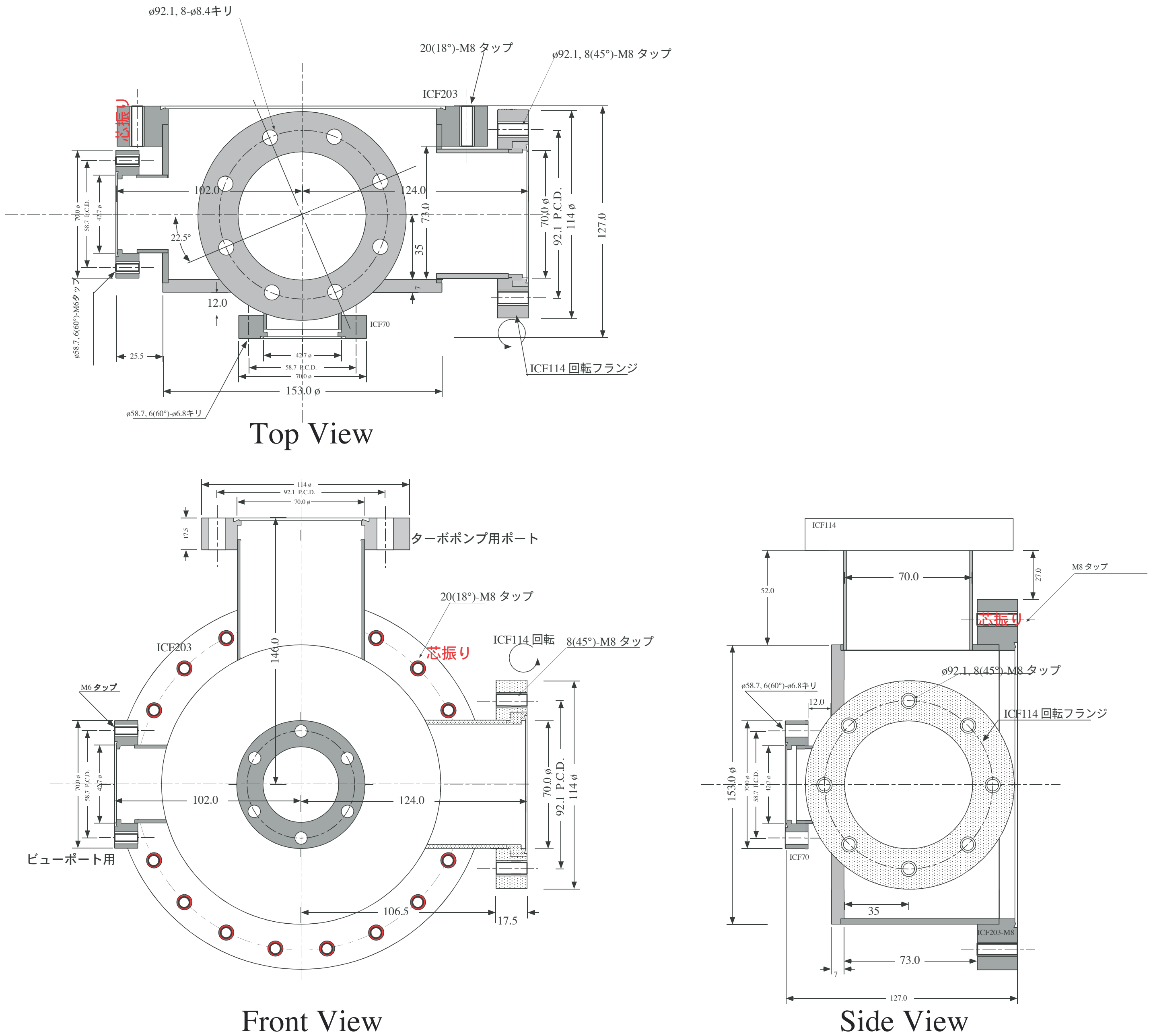


Figure 14: Drawing of vacuum chamber.

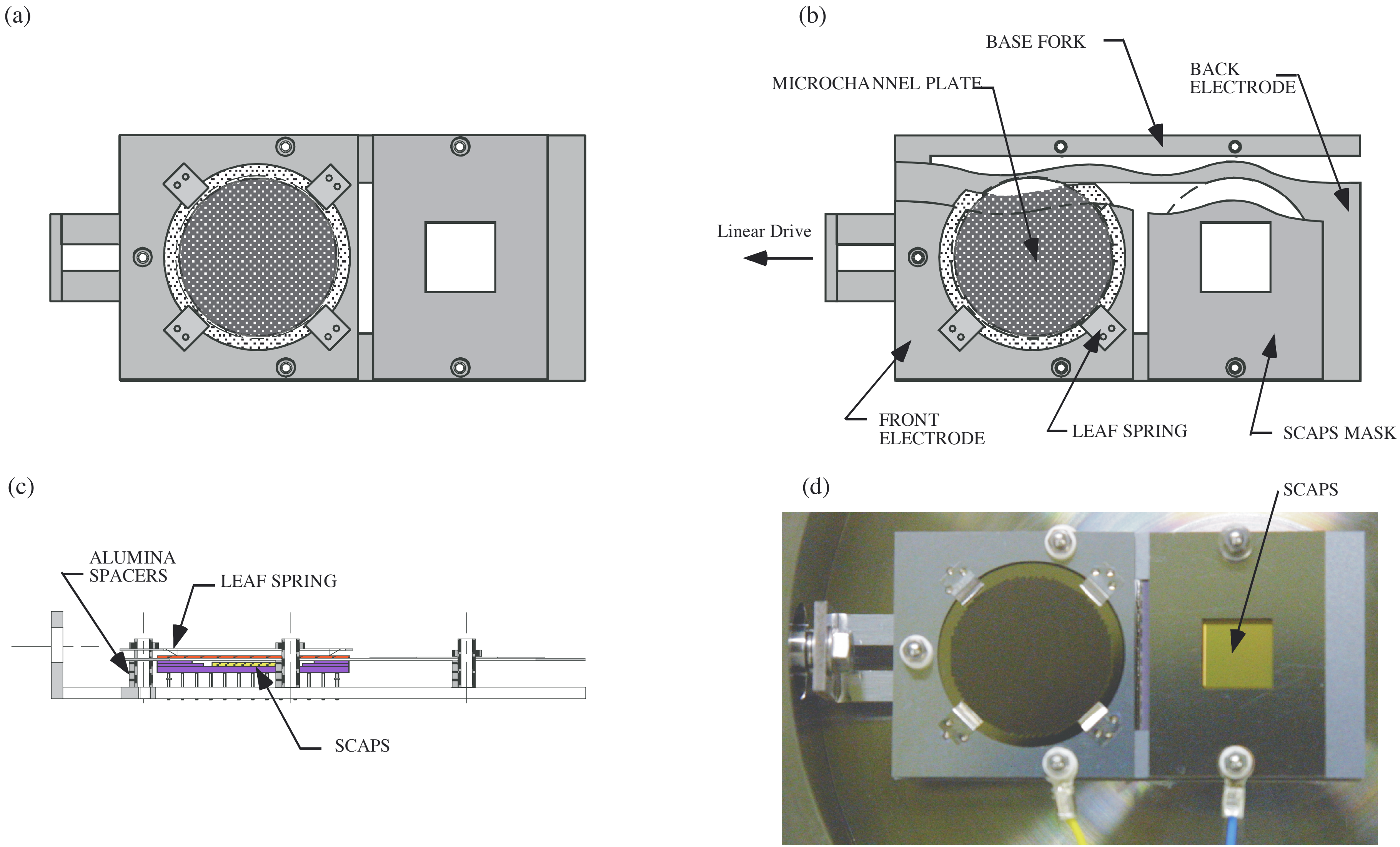


Figure 15: Schematic drawing of MCP carriage. (a)Top view (b)Top view with peeling plates. (c)Cross-sectional view shown with the position of SCAPS in high speed measurement mode. (d)MCP carriage shown with the position of SCAPS in high precision measurement mode. MCP is biasted between FRONT ELECTRODE via LEAF SPRINGs and BACK ELECTRODE. BACK ELECTRODE and SCAPS MASK are the same potential.

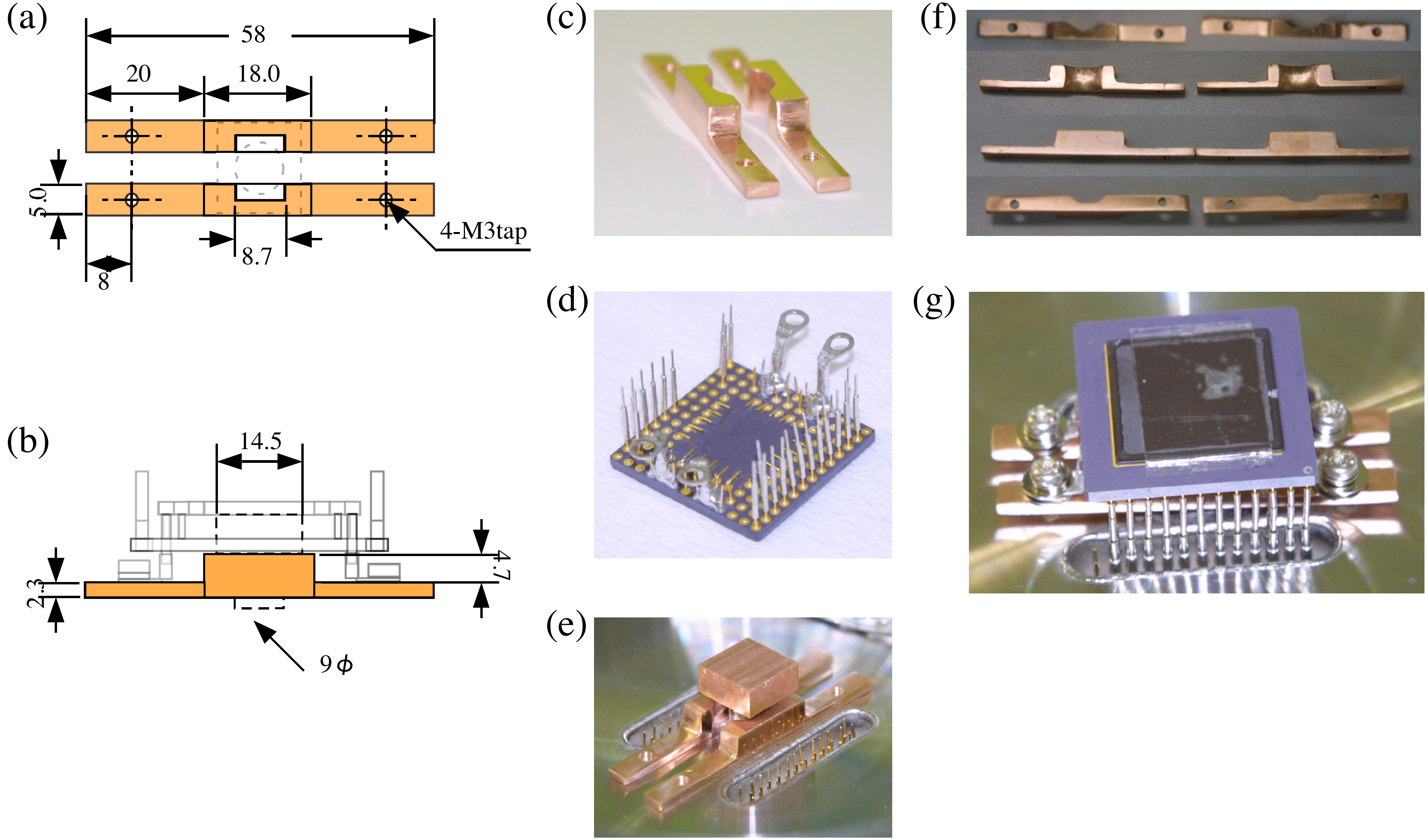


Figure 21: (a)Top view of fixing bracket layout, (b)side view, (c)appearance of fixing brackets, (d)worked SCAPS with crimping terminals and sockets, (e)cold finger and fixing brackets on hybrid chamber, (f) fixing brackets, (g) completion with cover shield.

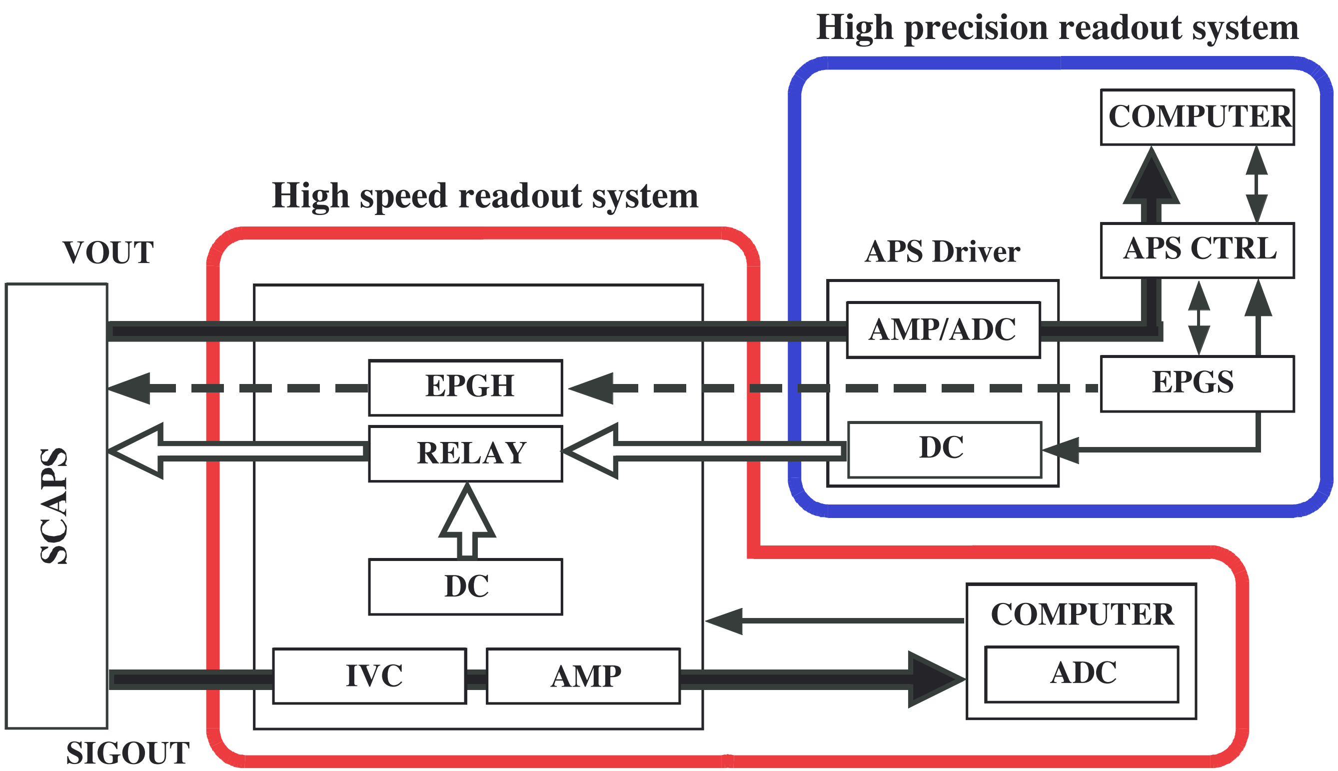


Figure 22: Block diagram of electronic circuit of the hybrid ion imaging system consists of high speed readout system and high precision readout system. Bold arrows mean data flows of output signal from two different output parts of **SCAPS**, **VOUT** and **SIGOUT**. Dotted, outline and thine arrows mean pulse lines, voltage supplies and control signals respectively. Brevity code written in a box indicates following means:**ADC** A/D converter, **AMP** amplifire, **APS CTRL** APS controller, **DC** voltage supply, **EPGH** enhanced pulse generator for hybrid, **EPGS** enhanced pulse generator for SUSHI, **IVC** current-voltage converter, **RELAY** mechanical relay.

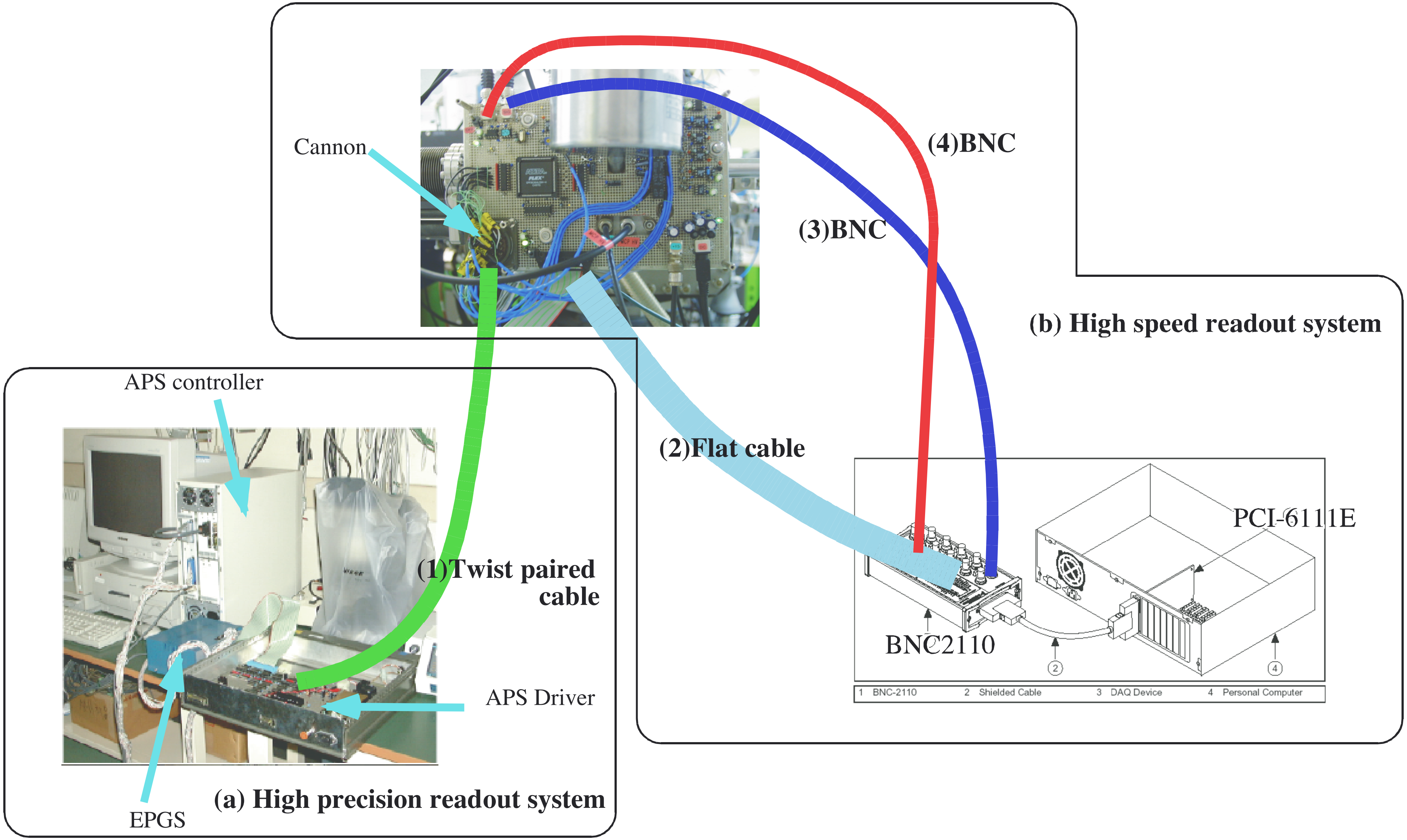


Figure 23: Physical connection layout of hybrid ion imaging system.

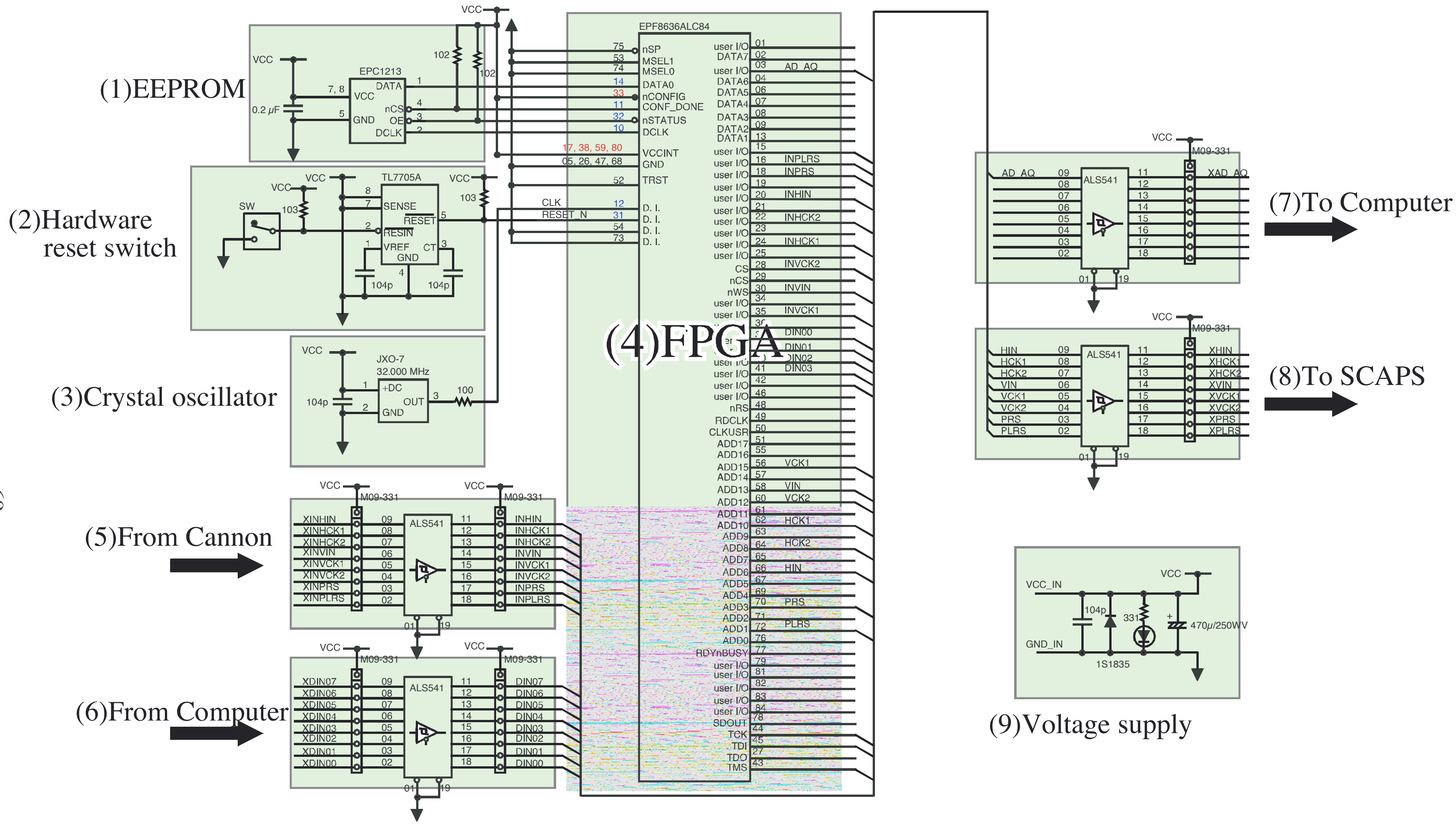


Figure 24: Layout of Enhanced pulse generator for Hybrid (EPGH).(1)EEPROM register VHDL program, (2)hardware reset switch to stop overdrive, (3)crystal oscillator to generate basic pulse, (4) Field programmable gate array (FPGA), (5) buffers for the signals from high precision readout system. the interface is cannon.(6) buffers for the signals from the hostcomputer of high-speed readout system. the interface is cannon 26pin flat cable, (7)line driver for the timing pulse for A/D converter, (8)line drivers for driving pulses to SCAPS.

```
----------------------------------------------------------------------------------------
-- ENHANCED PULSE GENERATOR FOR APS
--		1997/10/08		tky		STARTS EPGA FOR APS DEVELOPMENT
--		1997/12/23		tky		ADD STATE MACHINE
--		1997/12/24		tky		ADD CLK_SPEED
--		1998/06/04		tky		CLK(1MHz) -> CLK(16MHz)
--		1998/07/22		tky		REMOVE NEXT_STT, INIT_ST
--		1998/08/10		tky		ADD TURBO FUNCTION
--		1998/08/19		tky		ALWAY PULSING H-CLK
--		2000/03/29		tky		CONT1, CONT2, ETC WILL CHANGE ONLY AT FRAME START
--		2000/08/08		tky		2 TIME QUICK MOVEMENT
--		2000/08/08		tky		FAST MONITOR MODE (TURBO FUNCTION MODIFIED)
-- ENHANCED PULSE GENERATOR FOR SUSHI0100
--		2001/06/22		tky		NEW DEVELOPMENT
-- ENHANCED PULSE GENERATOR FOR Hybrid SUSHI0100
--		2003/07/23		sak		SWITCH PHOTO-VIDEO MODE
---------------------------------------,-------------------------------------------------

library IEEE;
use IEEE.std_logic_1164.all;
use IEEE.std_logic_unsigned.all;
use IEEE.std_logic_arith.all;

entity epgh is
		port(
				clk				:		in std_logic;
				rst_n				:		in std_logic;
				scan_flg_in			:		in std_logic;
--				adp_flg_in			:		in std_logic;
				photo_video_flg_in		:		in std_logic;
				reset_mode_in			:		in std_logic_vector(1 downto 0);
--				clk_speed_in			:		in std_logic_vector(3 downto 0);
--				scan_mode_in			:		in std_logic_vector(3 downto 0);
				clk_speed_in			:		in std_logic_vector(1 downto 0);
				scan_mode_in			:		in std_logic;
				hck1_in				:		in std_logic;
				hck2_in				:		in std_logic;
				vck1_in				:		in std_logic;
				vck2_in				:		in std_logic;
				hin_in				:		in std_logic;
				vin_in				:		in std_logic;
				prs_in				:		in std_logic;
				plrs_in				:		in std_logic;
--				rsvd_in_0			:		in std_logic;
				hck1, hck2, hin			:		out std_logic;
				vck1, vck2, vin			:		out std_logic;
				prs, plrs			:		out std_logic;
				ad_aq				:		out std_logic
--				rsvd_out_0			:		out std_logic;
--				rsvd_out_1			:		out std_logic;
--				rsvd_out_2			:		out std_logic
		);
end epgh;

architecture arch_epgh of epgh is

		constant	Hig		:		std_logic				:= '1';
		constant	Low		:		std_logic				:= '0';
		constant	ZERO_01_00	:		std_logic_vector( 1 downto 0)	:= "00";
		constant	ZERO_02_00	:		std_logic_vector( 2 downto 0)	:= "000";
		constant	ZERO_03_00	:		std_logic_vector( 3 downto 0)	:= "0000";
		constant	ZERO_04_00	:		std_logic_vector( 4 downto 0)	:= "00000";
		constant	ZERO_05_00	:		std_logic_vector( 5 downto 0)	:= "000000";
		constant	ZERO_06_00	:		std_logic_vector( 6 downto 0)	:= "0000000";
		constant	ZERO_07_00	:		std_logic_vector( 7 downto 0)	:= "00000000";
		constant	ZERO_08_00	:		std_logic_vector( 8 downto 0)	:= "000000000";
		constant	ZERO_09_00	:		std_logic_vector( 9 downto 0)	:= "0000000000";
		constant	ZERO_10_00	:		std_logic_vector(10 downto 0)	:= "00000000000";
		constant	ZERO_11_00	:		std_logic_vector(11 downto 0)	:= "000000000000";
```

Figure 25: Code for EPGH (1/8)

```
	constant	V_VCK2_UP	:	std_logic_vector(11 downto 0)	:= "000000001000";
	constant	V_VCK2_DWN	:	std_logic_vector(11 downto 0)	:= "000000010000";
	constant	V_VCK1_UP	:	std_logic_vector(11 downto 0)	:= "000000011000";
	constant	H_CNT_END_M	:	std_logic_vector(11 downto 0)	:= "000000011111";
	constant	H_IN_UP	:	std_logic_vector(11 downto 0)	:= "000100000000";
	constant	H_IN_DWN	:	std_logic_vector(11 downto 0)	:= "000100000100";
--	constant	H_PXL_000	:	std_logic_vector(11 downto 0)	:= "000100000111";
	constant	H_PXL_000	:	std_logic_vector(11 downto 0)	:= "000100001000";
	constant	H_PXL_076	:	std_logic_vector(11 downto 0)	:= "001000111000";
	constant	H_PXL_152	:	std_logic_vector(11 downto 0)	:= "001101101000";
	constant	H_PXL_456	:	std_logic_vector(11 downto 0)	:= "100000101000";
	constant	H_PXL_523	:	std_logic_vector(11 downto 0)	:= "100101011000";

	constant	H_PXL_608	:	std_logic_vector(11 downto 0)	:= "101010001000";
	constant	H_CNT_END_F	:	std_logic_vector(11 downto 0)	:= "101011111111";
--	constant	H_CNT_END_F	:	std_logic_vector(11 downto 0)	:= "010000011111";	-- FOR DEBUG

	constant	V_IN_UP	:	std_logic_vector( 9 downto 0)	:= "0000011111";
	constant	V_PXL_000	:	std_logic_vector( 9 downto 0)	:= "0000100000";
	constant	V_PXL_072	:	std_logic_vector( 9 downto 0)	:= "0001101000";
	constant	V_PXL_144	:	std_logic_vector( 9 downto 0)	:= "0010110000";
	constant	V_PXL_431	:	std_logic_vector( 9 downto 0)	:= "0111001111";
	constant	V_PXL_432	:	std_logic_vector( 9 downto 0)	:= "0111010000";
	constant	V_PXL_504	:	std_logic_vector( 9 downto 0)	:= "1000011000";
	constant	V_PXL_575	:	std_logic_vector( 9 downto 0)	:= "1001011111";
	constant	V_CNT_END	:	std_logic_vector( 9 downto 0)	:= "1001100000";

	constant	PLRS_SHORT_UP	:	std_logic_vector(11 downto 0)	:= "000000001000";
	constant	PLRS_SHORT_DWN	:	std_logic_vector(11 downto 0)	:= "000000010000";

--	constant	SPEED_0	:	std_logic_vector( 3 downto 0)	:= "0000";
--	constant	SPEED_1	:	std_logic_vector( 3 downto 0)	:= "0001";
--	constant	SPEED_2	:	std_logic_vector( 3 downto 0)	:= "0010";
--	constant	SPEED_3	:	std_logic_vector( 3 downto 0)	:= "0011";
--	constant	SPEED_4	:	std_logic_vector( 3 downto 0)	:= "0100";
--	constant	SPEED_5	:	std_logic_vector( 3 downto 0)	:= "0101";
--	constant	SPEED_6	:	std_logic_vector( 3 downto 0)	:= "0110";
--	constant	SPEED_7	:	std_logic_vector( 3 downto 0)	:= "0111";
--	constant	SPEED_8	:	std_logic_vector( 3 downto 0)	:= "1000";
--	constant	SPEED_9	:	std_logic_vector( 3 downto 0)	:= "1001";
--	constant	SPEED_A	:	std_logic_vector( 3 downto 0)	:= "1010";
--	constant	SPEED_B	:	std_logic_vector( 3 downto 0)	:= "1011";
--	constant	SPEED_C	:	std_logic_vector( 3 downto 0)	:= "1100";
--	constant	SPEED_D	:	std_logic_vector( 3 downto 0)	:= "1101";
--	constant	SPEED_E	:	std_logic_vector( 3 downto 0)	:= "1110";
--	constant	SPEED_F	:	std_logic_vector( 3 downto 0)	:= "1111";
	constant	SPEED_0	:	std_logic_vector( 1 downto 0)	:= "00";
	constant	SPEED_1	:	std_logic_vector( 1 downto 0)	:= "01";
	constant	SPEED_2	:	std_logic_vector( 1 downto 0)	:= "10";
	constant	SPEED_3	:	std_logic_vector( 1 downto 0)	:= "11";

--	constant	CNT_002M_MAX	:	std_logic_vector( 8 downto 0)	:= "000000001";
--	constant	CNT_001M_MAX	:	std_logic_vector( 8 downto 0)	:= "000000011";
--	constant	CNT_800K_MAX	:	std_logic_vector( 8 downto 0)	:= "000000100";
--	constant	CNT_500K_MAX	:	std_logic_vector( 8 downto 0)	:= "000000111";
--	constant	CNT_250K_MAX	:	std_logic_vector( 8 downto 0)	:= "000001111";
--	constant	CNT_125K_MAX	:	std_logic_vector( 8 downto 0)	:= "000011111";
--	constant	CNT_080K_MAX	:	std_logic_vector( 8 downto 0)	:= "000110001";
--	constant	CNT_040K_MAX	:	std_logic_vector( 8 downto 0)	:= "001100011";
--	constant	CNT_020K_MAX	:	std_logic_vector( 8 downto 0)	:= "011000111";
--	constant	CNT_010K_MAX	:	std_logic_vector( 8 downto 0)	:= "110001111";
--	constant	CNT_RESERVD1	:	std_logic_vector( 8 downto 0)	:= "011000111";
--	constant	CNT_RESERVD2	:	std_logic_vector( 8 downto 0)	:= "011000111";
--	constant	CNT_RESERVD3	:	std_logic_vector( 8 downto 0)	:= "011000111";
--	constant	CNT_RESERVD4	:	std_logic_vector( 8 downto 0)	:= "011000111";
--	constant	CNT_RESERVD5	:	std_logic_vector( 8 downto 0)	:= "011000111";
--	constant	CNT_RESERVD6	:	std_logic_vector( 8 downto 0)	:= "011000111";
	constant	CNT_004M_MAX	:	std_logic_vector( 8 downto 0)	:= "000000001";
	constant	CNT_002M_MAX	:	std_logic_vector( 8 downto 0)	:= "000000011";
	constant	CNT_500K_MAX	:	std_logic_vector( 8 downto 0)	:= "000001111";
	constant	CNT_020K_MAX	:	std_logic_vector( 8 downto 0)	:= "110001111"
```

Figure 25: Code for EPGH (2/8)

```
		constant	RST_MODE_0		:		std_logic_vector( 1 downto 0)		:= "00";
		constant	RST_MODE_1		:		std_logic_vector( 1 downto 0)		:= "01";
		constant	RST_MODE_2		:		std_logic_vector( 1 downto 0)		:= "10";
		constant	RST_MODE_3		:		std_logic_vector( 1 downto 0)		:= "11";

--		constant	SCN_MODE_0		:		std_logic_vector( 3 downto 0)		:= "0000";
--		constant	SCN_MODE_1		:		std_logic_vector( 3 downto 0)		:= "0001";
--		constant	SCN_MODE_2		:		std_logic_vector( 3 downto 0)		:= "0010";
--		constant	SCN_MODE_3		:		std_logic_vector( 3 downto 0)		:= "0011";
--		constant	SCN_MODE_4		:		std_logic_vector( 3 downto 0)		:= "0100";
--		constant	SCN_MODE_5		:		std_logic_vector( 3 downto 0)		:= "0101";
--		constant	SCN_MODE_6		:		std_logic_vector( 3 downto 0)		:= "0110";
--		constant	SCN_MODE_7		:		std_logic_vector( 3 downto 0)		:= "0111";
--		constant	SCN_MODE_8		:		std_logic_vector( 3 downto 0)		:= "1000";
--		constant	SCN_MODE_9		:		std_logic_vector( 3 downto 0)		:= "1001";
--		constant	SCN_MODE_A		:		std_logic_vector( 3 downto 0)		:= "1010";
--		constant	SCN_MODE_B		:		std_logic_vector( 3 downto 0)		:= "1011";
--		constant	SCN_MODE_C		:		std_logic_vector( 3 downto 0)		:= "1100";
--		constant	SCN_MODE_D		:		std_logic_vector( 3 downto 0)		:= "1101";
--		constant	SCN_MODE_E		:		std_logic_vector( 3 downto 0)		:= "1110";
--		constant	SCN_MODE_F		:		std_logic_vector( 3 downto 0)		:= "1111";

		type		scan_state is (IDLE0_ST, IDLE1_ST, IDLE2_ST, SCAN_ST);

		signal		stt_rg			:		scan_state;

		signal		v_counter		:		std_logic_vector( 9 downto 0);
		signal		h_counter		:		std_logic_vector(11 downto 0);

		signal		clk_h			:		std_logic;
		signal		rst			:		std_logic;

		signal		scan_flg		:		std_logic;
--		signal		adp_flg			:		std_logic;
		signal		photo_video_flg		:		std_logic;
		signal		reset_mode		:		std_logic_vector(1 downto 0);
--		signal		clk_speed		:		std_logic_vector(3 downto 0);
--		signal		scan_mode		:		std_logic_vector(3 downto 0);
		signal		clk_speed		:		std_logic_vector(1 downto 0);
		signal		scan_mode		:		std_logic;

		signal		clk_counter		:		std_logic_vector(8 downto 0);
		signal		clk_cnt_max		:		std_logic_vector(8 downto 0);

		signal		h_ad_ena		:		std_logic;
		signal		v_ad_ena		:		std_logic;
		signal		const_scan_flg		:		std_logic;

begin

-----------------------------------------------------------------------
--			INVERSION OF RESET_N
-----------------------------------------------------------------------
		process(rst_n, rst) begin
			if(rst_n = Low)
				then		rst <= Hig;
				else		rst <= Low;
			end if;
		end process;


-----------------------------------------------------------------------
--			INPUT BUFFER
-----------------------------------------------------------------------
--		process(rst, clk, scan_flg, adp_flg, reset_mode, clk_speed) begin
		process(rst, clk, scan_flg, reset_mode, clk_speed, photo_video_flg) begin
			if(rst = Hig) then
				scan_flg		<= Low;
--				adp_flg			<= Low;
				reset_mode		<= ZERO_01_00;
--				clk_speed		<= ZERO_03_00;
--				scan_mode		<= ZERO_03_00;
				clk_speed		<= ZERO_01_00;
				scan_mode		<= Low;
```

Figure 25: Code for EPGH (3/8)

```
--                  rsvd_out_0      <= Low;                 -- FOR SYSTEM RESERVATION
--                  rsvd_out_1      <= Low;                 -- FOR SYSTEM RESERVATION
--                  rsvd_out_2      <= Low;                 -- FOR SYSTEM RESERVATION

            elsif(clk'event and clk = Hig) then
--                  adp_flg         <= adp_flg_in;
                    if(stt_rg = IDLE0_ST or stt_rg = IDLE1_ST or stt_rg = IDLE2_ST) then
--                      adp_flg             <= adp_flg_in;
                        photo_video_flg     = photo_video_flg_in;
                        scan_flg            = scan_flg_in;
                        reset_mode          = reset_mode_in;
                        clk_speed           = clk_speed_in;
                        scan_mode           = scan_mode_in;
                    end if;

--                  rsvd_out_0      <= rsvd_in_0;       -- FOR SYSTEM RESERVATION
--                  rsvd_out_1      <= rsvd_in_0;       -- FOR SYSTEM RESERVATION
--                  rsvd_out_2      <= rsvd_in_0;       -- FOR SYSTEM RESERVATION

            end if;
        end process;

-------------------------------------------------------------------------
--          SPEED CONTROL SUBSTITUTION
-------------------------------------------------------------------------
        process(rst, clk, clk_speed) begin
            if(rst = Hig) then
                    clk_cnt_max <= ZERO_08_00;
            elsif(clk'event and clk = Hig) then
                    if( ((h_ad_ena = Hig) and (v_ad_ena = Hig)) or (const_scan_flg = Hig) ) then
                        if(clk_speed = SPEED_0)then     clk_cnt_max <= CNT_004M_MAX;
                        elsif(clk_speed = SPEED_1)      then    clk_cnt_max <= CNT_002M_MAX;
                        elsif(clk_speed = SPEED_2)      then    clk_cnt_max <= CNT_500k_MAX;
                        elsif(clk_speed = SPEED_3)      then    clk_cnt_max <= CNT_020k_MAX;

--                      if(clk_speed = SPEED_0)then     clk_cnt_max <= CNT_002M_MAX;
--                      elsif(clk_speed = SPEED_1)      then    clk_cnt_max <= CNT_001M_MAX;
--                      elsif(clk_speed = SPEED_2)      then    clk_cnt_max <= CNT_800K_MAX;
--                      elsif(clk_speed = SPEED_3)      then    clk_cnt_max <= CNT_500K_MAX;
--                      elsif(clk_speed = SPEED_4)      then    clk_cnt_max <= CNT_250K_MAX;
--                      elsif(clk_speed = SPEED_5)      then    clk_cnt_max <= CNT_125K_MAX;
--                      elsif(clk_speed = SPEED_6)      then    clk_cnt_max <= CNT_080K_MAX;
--                      elsif(clk_speed = SPEED_7)      then    clk_cnt_max <= CNT_040K_MAX;
--                      elsif(clk_speed = SPEED_8)      then    clk_cnt_max <= CNT_020K_MAX;
--                      elsif(clk_speed = SPEED_9)      then    clk_cnt_max <= CNT_010K_MAX;
--                      elsif(clk_speed = SPEED_A)      then    clk_cnt_max <= CNT_RESERVD1;
--                      elsif(clk_speed = SPEED_B)      then    clk_cnt_max <= CNT_RESERVD2;
--                      elsif(clk_speed = SPEED_C)      then    clk_cnt_max <= CNT_RESERVD3;
--                      elsif(clk_speed = SPEED_D)      then    clk_cnt_max <= CNT_RESERVD4;
--                      elsif(clk_speed = SPEED_E)      then    clk_cnt_max <= CNT_RESERVD5;
--                      elsif(clk_speed = SPEED_F)      then    clk_cnt_max <= CNT_RESERVD6;
--                      else                                    clk_cnt_max <= CNT_020K_MAX;
                        end if;
                    else                                clk_cnt_max         <= CNT_002M_MAX;
                    end if;
            end if;
        end process;

-------------------------------------------------------------------------
--          CLK_H GENERATOR
-------------------------------------------------------------------------
        process(rst, clk, clk_counter) begin
            if(rst = Hig) then
                    clk_counter <= ZERO_08_00;
                    clk_h <= Low;
            elsif(clk'event and clk = Hig) then
                    if( clk_counter >= clk_cnt_max ) then
                        clk_counter <= ZERO_08_00;
                        clk_h <=Hig;
                    else
                        clk_counter <= clk_counter + 1;
                        clk_h <= Low;
                    end if;
            end if;
        end process;
```

Figure 25: Code for EPGH (4/8)

```
-----------------------------------------------------------------------
--                              DESCRIPTION OF H_COUNTER, V_COUNTER AND STATE MACHINE
-----------------------------------------------------------------------
                process(rst, clk_h) begin
                        if(rst = Hig) then
                                v_counter   <= ZERO_09_00;
--                              v_counter   <= "0000100000";                -- FOR DEBUG
--                              v_counter   <= "0111001110";                -- FOR DEBUG
--                              v_counter   <= "1001011110";                -- FOR DEBUG
                                h_counter   <= ZERO_11_00;
--                              h_counter   <= "000000000000";              -- FOR DEBUG
                                stt_rg                  <= IDLE0_ST;
                        elsif(clk_h'event and clk_h = Hig) then
                                case stt_rg is
                                ---------------------------------------------------
                                when IDLE0_ST =>
                                                stt_rg <= IDLE1_ST;
                                ---------------------------------------------------
                                when IDLE1_ST =>
                                                stt_rg <= IDLE2_ST;
                                ---------------------------------------------------
                                when IDLE2_ST =>
                                        if(scan_flg =  Hig) then
                                                stt_rg <= SCAN_ST;
                                        else                                                    -- STOP MOTION
                                                stt_rg <= IDLE2_ST;
                                        end if;
                                ---------------------------------------------------
                                when SCAN_ST =>
                                        if(             (h_counter >= H_CNT_END_F) or
                                                ((v_ad_ena = Low) and (h_counter >= H_CNT_END_M) and (const_scan_flg = Low))
                                                                                                -- PROGRESS V WITHOUT FULL H-SCAN
                                        ) then
                                                h_counter <= ZERO_11_00;
                                                if(v_counter >= V_CNT_END) then
                                                        v_counter <= ZERO_09_00;
                                                        stt_rg          <= IDLE0_ST;
                                                else
                                                        v_counter <= v_counter + 1;
                                                end if;
                                        else
                                                h_counter <= h_counter + 1;
                                        end if;
                                ---------------------------------------------------
                                when others =>
                                                stt_rg <= IDLE0_ST;
                                end case;
                        end if;
                end process;

-----------------------------------------------------------------------
--                              DRIVING PULSE GENERATOR
-----------------------------------------------------------------------
                process(rst, clk, photo_video_flg) begin
                        if(rst = Hig) then
                                hck1 <=  Low;           hck2 <=  Low;           hin  <=  Low;
                                vck1 <=  Low;           vck2 <=  Low;           vin  <=  Low;
                        elsif(clk'event and clk = Hig) then
                                if(photo_video_flg = Low) then
                                        hck1 <=         hck1_in;
                                        hck2 <= hck2_in;
                                        vck1 <= vck1_in;
                                        vck2 <= vck2_in;
                                        hin  <= hin_in;
                                        vin  <= vin_in;
                                elsif(photo_video_flg = Hig) then

--              clk_h           -_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_-_
--
--              h_cnt(0)        __--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--__--
--              h_cnt(1)        ____----____----____----____----____----____----____----____----____----____----____----____----____----____----
--              h_cnt(2)        ________--------________--------________--------________--------________--------________--------________--------
--              h_cnt(3)        ________________----------------________________----------------________________----------------________________
--
```

Figure 25: Code for EPGH (5/8)

```
--          #h_cnt      0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 4 4 4 4 4 4 4 4 4 4 5 5 5 5 5 5
--          #h_cnt      0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5
--
--          #pixel      00    01    02    03    04    05    06    07    08    09    10    11    12    13
--          hck1        --______--______--______--______--______--______--______--______--______--______--______--______--______--______
--          hck2        ____--______--______--______--______--______--______--______--______--______--______--______--______--______--__
--          ad_aq       ____--______--______--______--______--______--______--______--______--______--______--______--______--______--__


                        --hck1
                                    if(h_counter(1 downto 0) = "00")
                                        then hck1    <=  Hig;
                                        else hck1    <=  Low;
                                    end if;

                        --hck2
                                    if(h_counter(1 downto 0) = "10")
                                        then hck2    <=  Hig;
                                        else hck2    <=  Low;
                                    end if;

                        --hin
                                    if((h_counter >= H_IN_UP) and (h_counter < H_IN_DWN))
                                        then hin     <=  Hig;
                                        else hin     <=  Low;
                                    end if;

                        --vck1
                                    if(h_counter >= V_VCK1_UP)
                                        then vck1    <=  Hig;
                                        else vck1    <=  Low;
                                    end if;

                        --vck2
                                    if((h_counter >= V_VCK2_UP) and (h_counter < V_VCK2_DWN))
                                        then vck2    <=  Hig;
                                        else vck2    <=  Low;
                                    end if;

                        --vin
                                    if(v_counter = V_IN_UP)
                                        then vin     <=  Hig;
                                        else vin     <=  Low;
                                    end if;
                        end if;
                    end if;
            end process;

------------------------------------------------------------------------
--                      RESET PULSE GENERATOR
------------------------------------------------------------------------
            process(rst, clk, photo_video_flg) begin
                    if(rst = Hig) then
                                prs         <=  Low;
                                plrs        <=  Low;
                    elsif(clk'event and clk = Hig) then
                        if(photo_video_flg = Low) then
                                prs         <=  prs_in;
                                plrs        <=  plrs_in;
                        elsif(photo_video_flg = Hig) then
                                ---------------------------------------------
                                if(reset_mode = RST_MODE_0 ) then          --          LINE DRO COMPATIBLE WITH SCAPS
                                    prs         <= Low;
                                    if((h_counter >= PLRS_SHORT_UP) and (h_counter < PLRS_SHORT_DWN))
                                        then plrs <=  Hig;
                                        else plrs <=  Low;
                                    end if;
                                ---------------------------------------------
                                elsif(reset_mode = RST_MODE_1 ) then                   --          FULL TIME LINE DRO
                                    prs         <= Low;             plrs        <= Hig;
                                ---------------------------------------------
                                elsif(reset_mode = RST_MODE_2 ) then                   --          NDRO
                                    prs         <= Low;             plrs        <= Low;
```

Figure 25: Code for EPGH (6/8)

```
									---------------------------------------------
									elsif(reset_mode = RST_MODE_3 ) then				--		INDIVI RESET (TEST)
										plrs		<= Low;
										if(((v_counter(5 downto 0) = "100000") and (h_counter = "001001000111" or	h_counter = "001001001011" o
											h_counter = "001001010011" or	h_counter = "001001011011" or	h_counter = "001001100111" o
											h_counter = "001001101011" or	h_counter = "001001110011" or	h_counter = "001001111011" o
											h_counter = "001010000011"))
										or((v_counter(5 downto 0) = "100001") and (h_counter = "001001000011" or	h_counter = "001001010011" o
											h_counter = "001001011011" or	h_counter = "001001100011" or	h_counter = "001001110011" o
											h_counter = "001001111011"  ))
										or((v_counter(5 downto 0) = "100010") and (h_counter = "001001000111" or	h_counter = "001001010011" o
											h_counter = "001001011011" or	h_counter = "001001100111" or	h_counter = "001001110011" o
											h_counter = "001001110111" or	h_counter = "001001111011" or	h_counter = "001010000011"))
										or((v_counter(5 downto 0) = "100011") and (h_counter = "001001001011" or	h_counter = "001001010011" o
											h_counter = "001001011011" or	h_counter = "001001101011" or	h_counter = "001001110011" o
											h_counter = "001001111011" or	h_counter = "001010000011"	))
										or((v_counter(5 downto 0) = "100111") and (h_counter = "001001000011" or	h_counter = "001001000111" o
											h_counter = "001001010111" or	h_counter = "001001100011" or	h_counter = "001001100111" o
											h_counter = "001001110011" or	h_counter = "001001111011" or	h_counter = "001010000011"))
										) then
											prs		<= Hig;
										else
											prs		<= Low;
										end if;
									---------------------------------------------
--									else
--										prs		<= Low;	plrs		<= Low;
									end if;
								end if;
							end if;
						end process;

---------------------------------------------------------------------
--						AQUIRE PIXEL REGION
---------------------------------------------------------------------

						process(rst, clk, h_counter, v_counter, scan_mode, h_ad_ena, v_ad_ena) begin
							if(rst = Hig) then
									const_scan_flg <= Low;			h_ad_ena <= Low;				v_ad_ena <= Low;
							elsif(clk'event and clk = Hig) then
								---------------------------------------------
--								if(scan_mode = SCN_MODE_0 ) then				--		NORMAL AREA WITHOUT FAST SCAN [608H X 576V]
								if(scan_mode = Low ) then					--		NORMAL AREA WITHOUT FAST SCAN [608H X 576V]
									const_scan_flg <= Hig;
									if( (h_counter >=  H_PXL_000) and (h_counter < H_PXL_608) )		then h_ad_ena <= Hig; else h_ad_ena <= Low; end if;
									if( (v_counter >=  V_PXL_000) and (v_counter < V_CNT_END) )		then v_ad_ena <= Hig; else v_ad_ena <= Low; end if;
								---------------------------------------------
--								elsif(scan_mode = SCN_MODE_1 ) then				--		NORMAL AREA[608H X 576V]
--									const_scan_flg <= Low;
--									if( (h_counter >=  H_PXL_000) and (h_counter < H_PXL_608) )		then h_ad_ena <= Hig; else h_ad_ena <= Low; end if;
--									if( (v_counter >=  V_PXL_000) and (v_counter < V_CNT_END) )		then v_ad_ena <= Hig; else v_ad_ena <= Low; end if;
--								---------------------------------------------
--								elsif(scan_mode = SCN_MODE_2 ) then				--		PIXEL THINNED OUT[304H X 288V]
								elsif(scan_mode = Hig ) then					--		PIXEL THINNED OUT[304H X 288V]
									const_scan_flg <= Low;
									if( (h_counter >=  H_PXL_000) and (h_counter < H_PXL_608) and (h_counter(2) = Low))
															then h_ad_ena <= Hig; else h_ad_ena <= Low; end if;
									if( (v_counter >=  V_PXL_000) and (v_counter < V_CNT_END) and (v_counter(0) = Low))
															then v_ad_ena <= Hig; else v_ad_ena <= Low; end if;
								---------------------------------------------
--								elsif(		scan_mode = SCN_MODE_3 ) then			--		PIXEL THINNED OUT[152H X 144V]
--									const_scan_flg <= Low;
--									if( (h_counter >=  H_PXL_000) and (h_counter < H_PXL_608) and (h_counter(3 downto 2) = ZERO_01_00))
															then h_ad_ena <= Hig; else h_ad_ena <= Low; end if;
--									if( (v_counter >=  V_PXL_000) and (v_counter < V_CNT_END) and (v_counter(1 downto 0) = ZERO_01_00))
															then v_ad_ena <= Hig; else v_ad_ena <= Low; end if;
--								---------------------------------------------
--								elsif(		scan_mode = SCN_MODE_4 ) then			--		PIXEL THINNED OUT[076H X 072V]
--									const_scan_flg <= Low;
--									if( (h_counter >=  H_PXL_000) and (h_counter < H_PXL_608) and (h_counter(4 downto 2) = ZERO_02_00))
															then h_ad_ena <= Hig; else h_ad_ena <= Low; end if;
--									if( (v_counter >=  V_PXL_000) and (v_counter < V_CNT_END) and (v_counter(2 downto 0) = ZERO_02_00))
															then v_ad_ena <= Hig; else v_ad_ena <= Low; end if;
```

Figure 25: Code for EPGH (7/8)

```
--                                      ---------------------------------------------
--                                      elsif(    scan_mode = SCN_MODE_5 ) then              --        CENTRAL AREA[456H X 432V]
--                                                const_scan_flg <= Low;
--                                                if( (h_counter >=  H_PXL_076) and (h_counter < H_PXL_523) )          then h_ad_ena <= Hig; else h_ad_ena <= Low; end if;
--                                                if( (v_counter >=  V_PXL_072) and (v_counter < V_PXL_504) )          then v_ad_ena <= Hig; else v_ad_ena <= Low; end if;
--                                      ---------------------------------------------
--                                      elsif(    scan_mode = SCN_MODE_6 ) then              --        CENTRAL AREA[304H X 288V]
--                                                const_scan_flg <= Low;
--                                                if( (h_counter >=  H_PXL_152) and (h_counter < H_PXL_456) )          then h_ad_ena <= Hig; else h_ad_ena <= Low; end if;
--                                                if( (v_counter >=  V_PXL_144) and (v_counter < V_PXL_432) )          then v_ad_ena <= Hig; else v_ad_ena <= Low; end if;
--                                      ---------------------------------------------
--                                      elsif(    scan_mode = SCN_MODE_7 ) then              --        RESERVED
--                                                const_scan_flg <= Hig;       h_ad_ena <= Low;             v_ad_ena <= Low;
--                                      ---------------------------------------------
--                                      elsif(    scan_mode = SCN_MODE_8 ) then              --        RESERVED
--                                                const_scan_flg <= Hig;       h_ad_ena <= Low;             v_ad_ena <= Low;
--                                      ---------------------------------------------
--                                      elsif(    scan_mode = SCN_MODE_9 ) then              --        RESERVED
--                                                const_scan_flg <= Hig;       h_ad_ena <= Low;             v_ad_ena <= Low;
--                                      ---------------------------------------------
--                                      elsif(    scan_mode = SCN_MODE_A ) then              --        RESERVED
--                                                const_scan_flg <= Hig;       h_ad_ena <= Low;             v_ad_ena <= Low;
--                                      ---------------------------------------------
--                                      elsif(    scan_mode = SCN_MODE_B ) then              --        RESERVED
--                                                const_scan_flg <= Hig;       h_ad_ena <= Low;             v_ad_ena <= Low;
--                                      ---------------------------------------------
--                                      elsif(    scan_mode = SCN_MODE_C ) then              --        RESERVED
--                                                const_scan_flg <= Hig;       h_ad_ena <= Low;             v_ad_ena <= Low;
--                                      ---------------------------------------------
--                                      elsif(    scan_mode = SCN_MODE_D ) then              --        RESERVED
--                                                const_scan_flg <= Hig;       h_ad_ena <= Low;             v_ad_ena <= Low;
--                                      ---------------------------------------------
--                                      elsif(    scan_mode = SCN_MODE_E ) then              --        RESERVED
--                                                const_scan_flg <= Hig;       h_ad_ena <= Low;             v_ad_ena <= Low;
--                                      ---------------------------------------------
--                                      elsif(    scan_mode = SCN_MODE_F ) then              --        RESERVED
--                                                const_scan_flg <= Hig;       h_ad_ena <= Low;             v_ad_ena <= Low;
--                                      ---------------------------------------------
--                                      else
--                                                const_scan_flg <= Hig;       h_ad_ena <= Low;             v_ad_ena <= Low;
                                        end if;
                            end if;
              end process;

------------------------------------------------------------------------
--                          A/D PULSE GENERATOR
------------------------------------------------------------------------

              process(rst, clk, h_ad_ena, v_ad_ena, photo_video_flg) begin
                            if(rst = Hig) then
                                                ad_aq <= Low;
                            elsif(clk'event and clk = Hig) then
                                        if(photo_video_flg = Low) then
                                                ad_aq  <= Low;
                                        elsif(photo_video_flg = Hig) then
--                                              if((adp_flg = Hig) and (h_ad_ena = Hig) and (v_ad_ena = Hig) and (h_counter(1 downto 0) = "10"))
                                                if((h_ad_ena = Hig) and (v_ad_ena = Hig) and (h_counter(1 downto 0) = "10"))
                                                          then ad_aq <=  Hig;
                                                          else ad_aq <=  Low;
                                                end if;
                                        end if;
                            end if;
              end process;

end arch_epgh;
```

Figure 25: Code for EPGH (8/8)

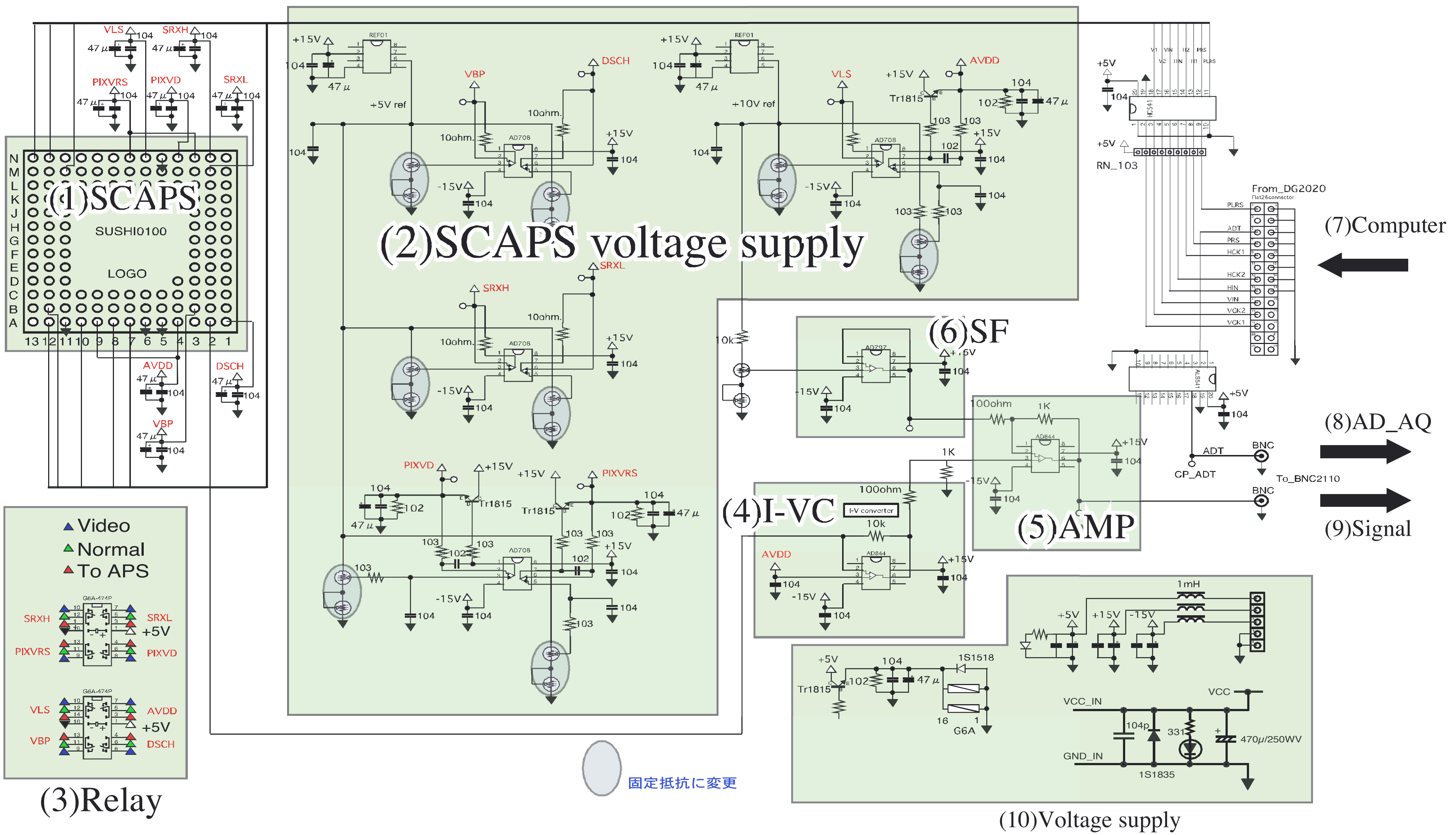


Figure 26: Layout of hybrid SCAPS driver. (1)SCAPS device can be attached on this driver for test, (2)voltage supply circuit for SCAPS, (3)Relays to select voltages the set of high-speed generated this boad or high precision generated by APS Driver, (4)current to voltage converter with AD844, (5)amplifire with AD844, (6)source follower with AD797. (7)digital signals from host computer, (8)A/D timing pulse called AD_AQ are output by BNC cable, (9)amplified signals are output by BNC cable.

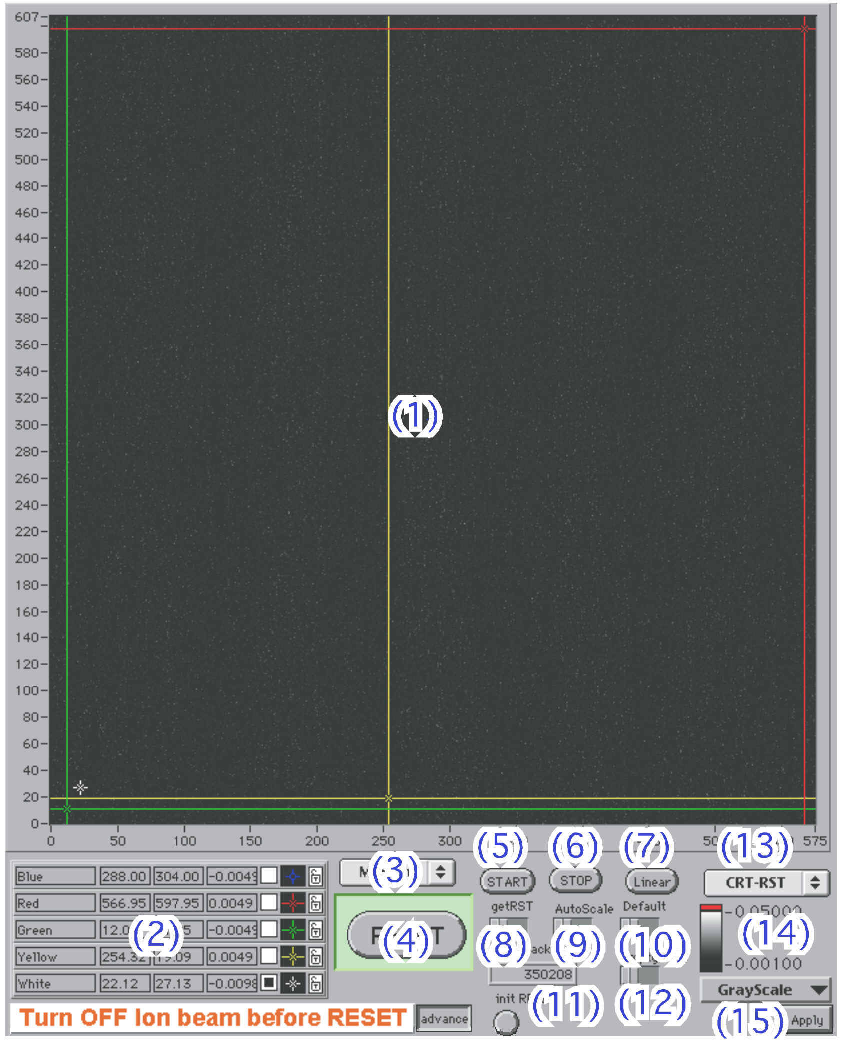


Figure 27: Interface of ION MONITOR. The functions of parts are as follows; (1)display image area, (2)marks, (3)bring a mark to the center of (1), (4)RESET button, (5)start button, (6)stop button, (7)selection switch to plot data as linear or logarithm, (8)get frame to memory, (9)auto scaling of image, (10)set default value of color range, (11)indicator of number of acquired data in FIFO, (12)set empty FIFO, (13)selection switch to plot the raw data or corrected data, (14)range of color, (15)selection switch of the color table.

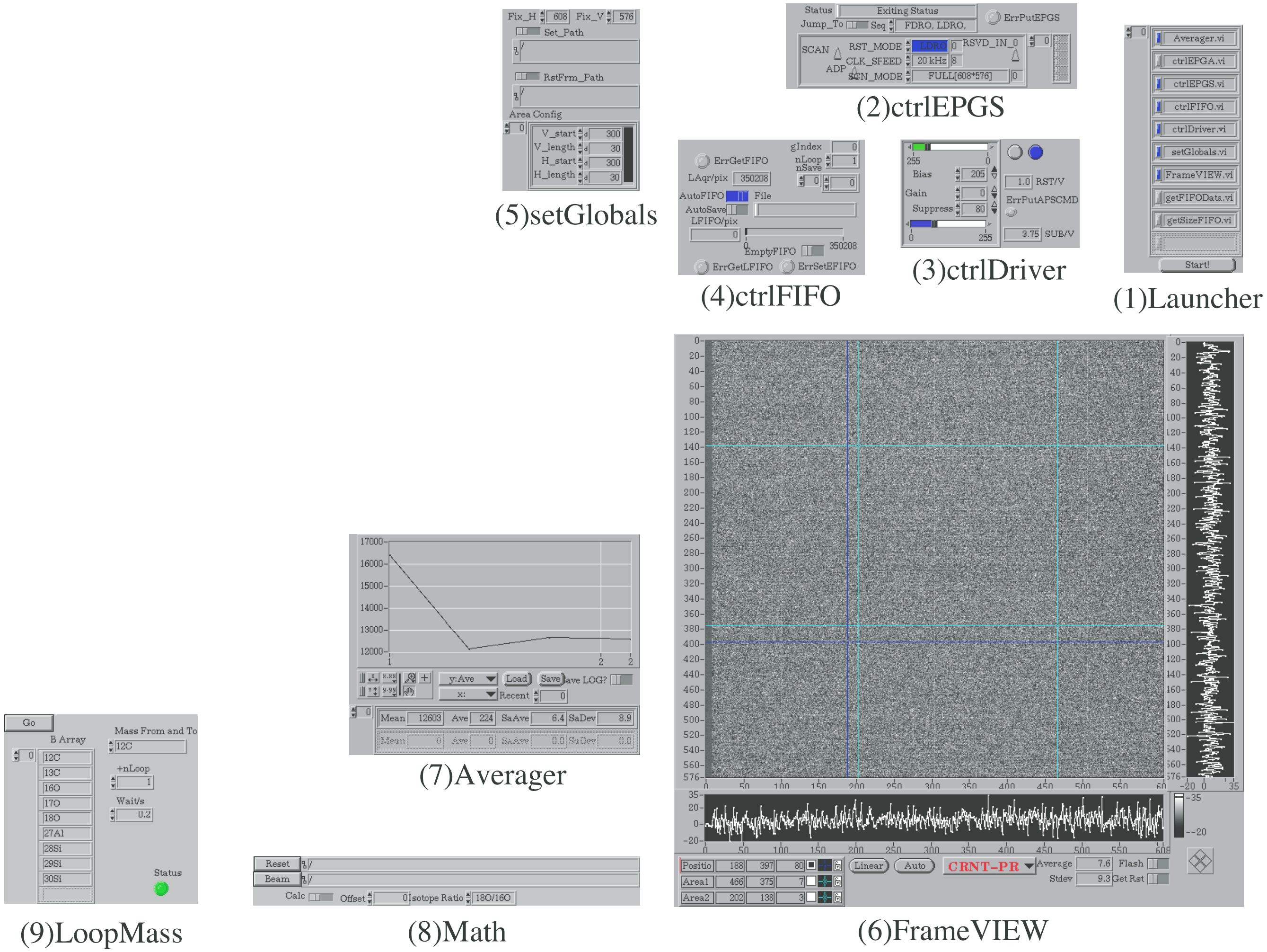


Figure 28: Interface of SUSHI-VIEW software package developed by Takuya Kunihiro. In high precision readout, this software run on SUN computer. (1)launcher, (2)control EPGS, (3)control APS driver, (4)control FIFO of APS controller. (5)set global variables, (6)display image area, (7)data logger of average value of image, (8)compute an informal isotopic ratio, (9) loop mass from a top to order the isotope list to minimize the effect of the hysteresis on the magnetic field.

(a) aps_chain_isotope

(b) aps_chain_frame

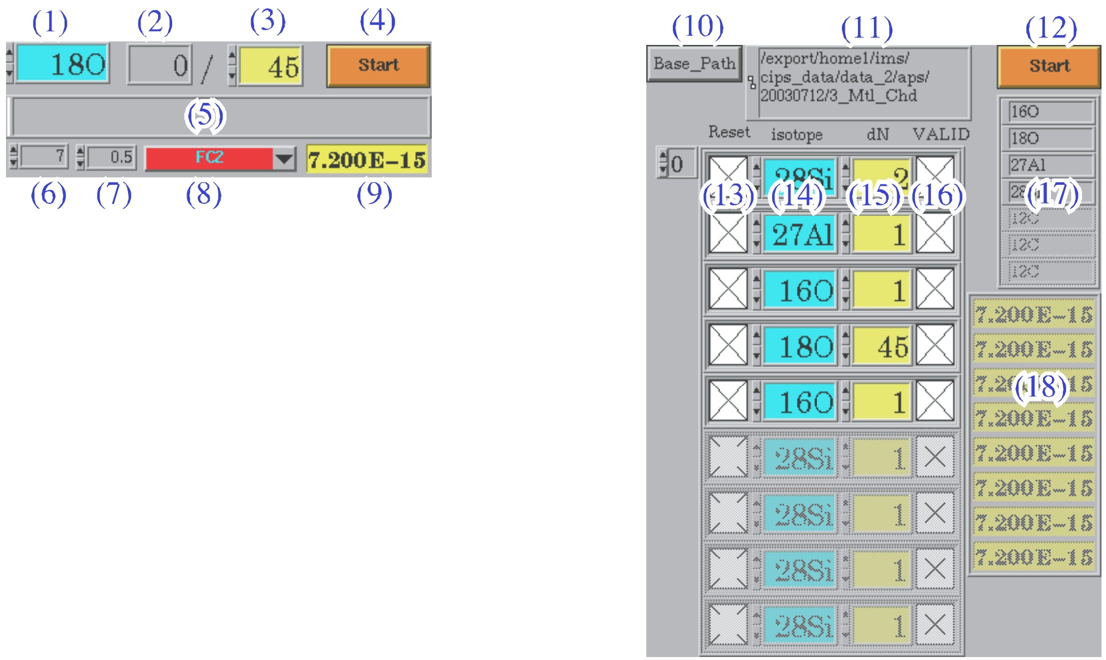


Figure 29: Interfaces of automation software APS-CHAIN. (a) named aps_chain_isotpe to measure one isotope and (b) named aps_chain_frame to measure multi-isotope with (a) as a function. The functions of parts are as follows; (1)measuring isotope, (2)indicator of current number of acquired frame, (3)total number of frame to acquire, (4)start button, (5)status message window, (6)sampling number of (8), (7)sampling time of (8), (8)selector to choose detector to measure total ion counts, (9)total count of incident ions detected by (8), (10)select button to choose base of save path, (11)base of save path, (12)start button, (13)-(16)list of measuring conditions, (13)reset or not before measure, (14)isotopes to measure, (15)number of acquiring frames, (16)valid condition same column, (17)list of isotopes for loop mass, (18)list of total counts measured at (9).

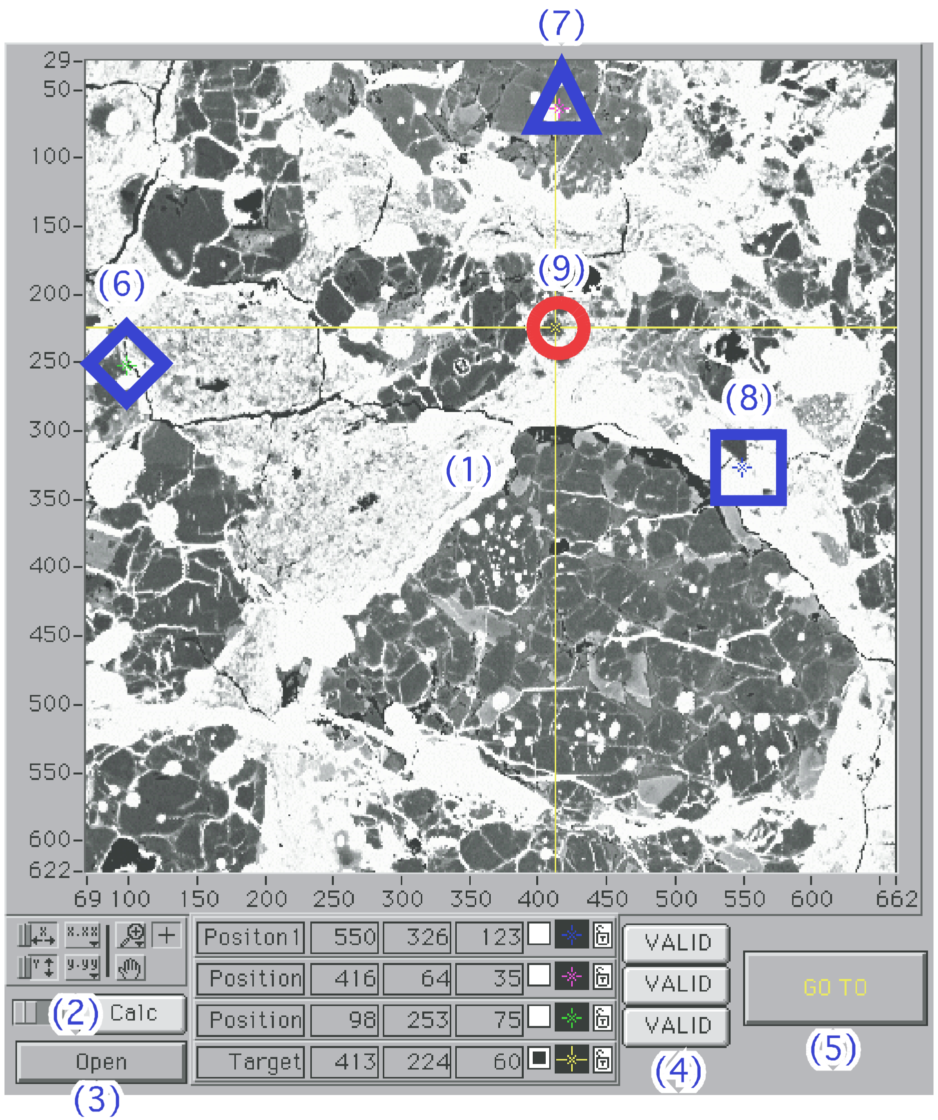


Figure 30: Interface of VIRTUAL STAGE SYSTEM for CIPS using affine transform. The functions of parts are as follows; (1)display image area, (2)calculation button (3)open filebutton, (4)set values to compute, (5)move sample stage of SIMS corresponding to (9), (6)(7)(8) reference points for affine paramaters, (9)target.

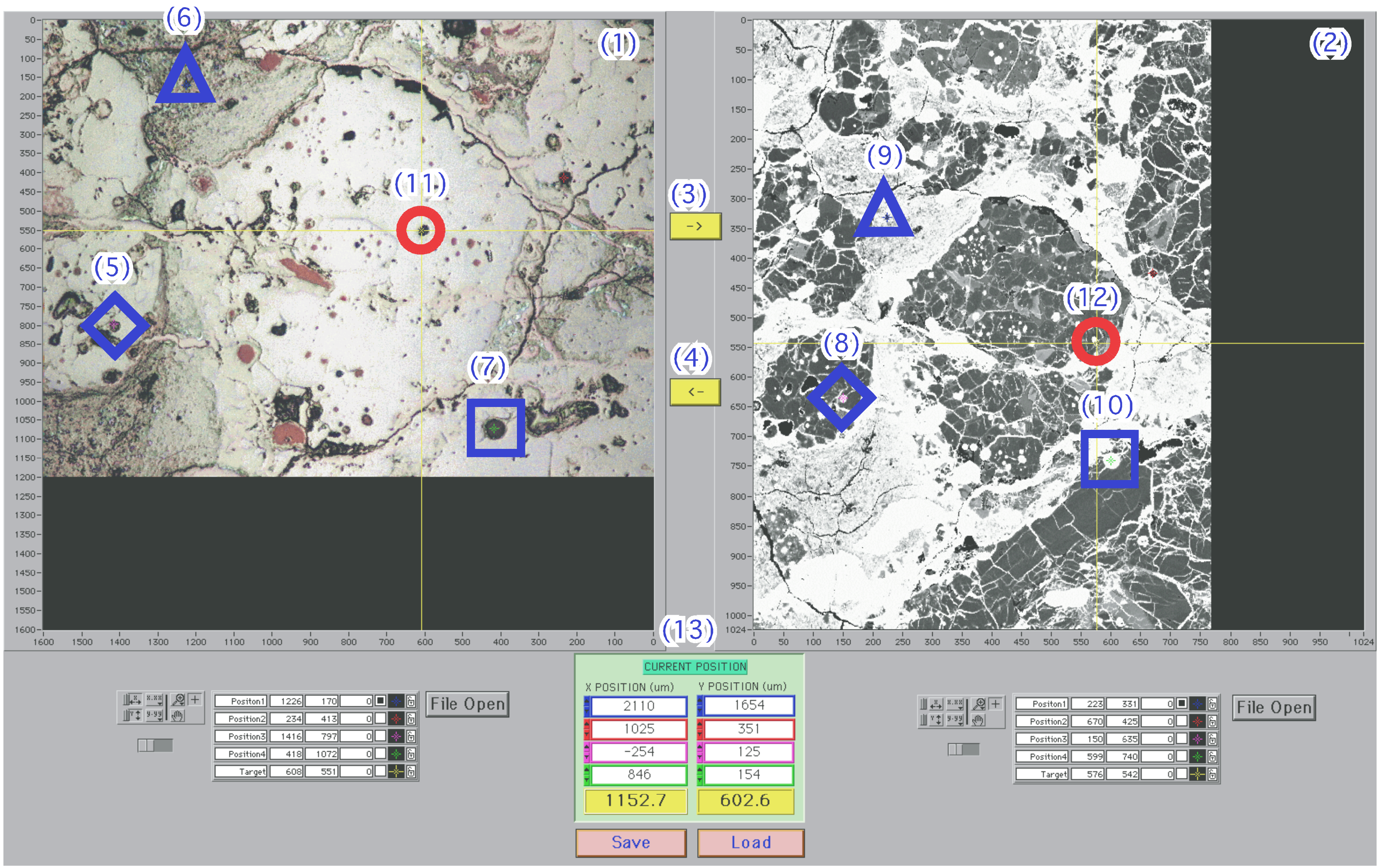


Figure 31: Interface of VIRTUAL STAGE SYSTEM using affine transform. The functions of parts are as follows; (1)(2)display image area,(3)(4)run button to transform coordinate only the target point (11) and (12)， (5)(6)(7)and (8)(9)(10)reference points for transformation parameters, the shapes indicate correspondence of each points. (11)(12)target point,(13)generated position value of sample stage in SIMS .

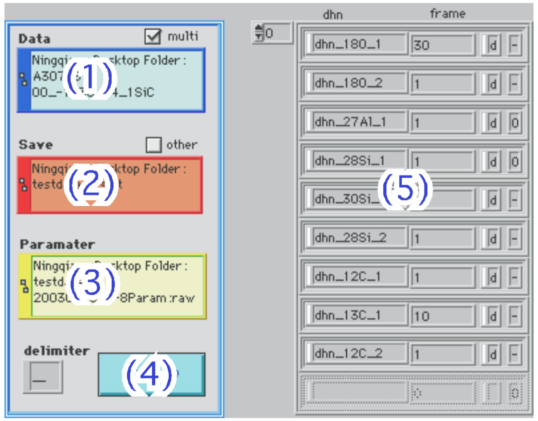


Figure 32: Interface of correction image generator N. The functions of parts are as follows; (1)data path witch response to multi, (2)save path, (3)path to directory including parameter files, (4)run button, (5)indicator of results.

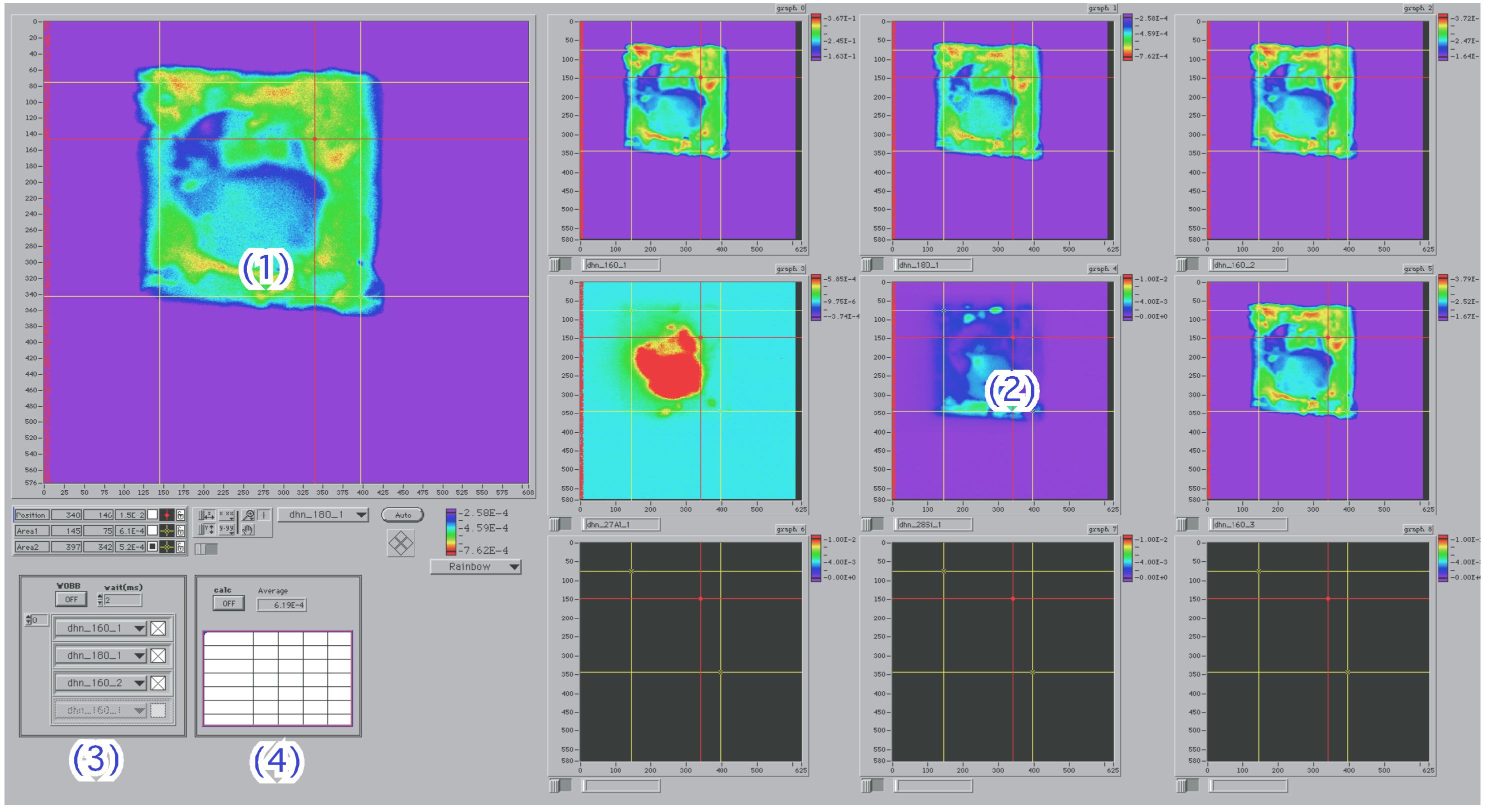


Figure 33: Interface of MULTI VIEWER. The functions of parts are as follows; (1)working image area, (2)thumbnails operate simultaneously with (1), (3)slide show selected images at certain interval, (4)data list of selected area.

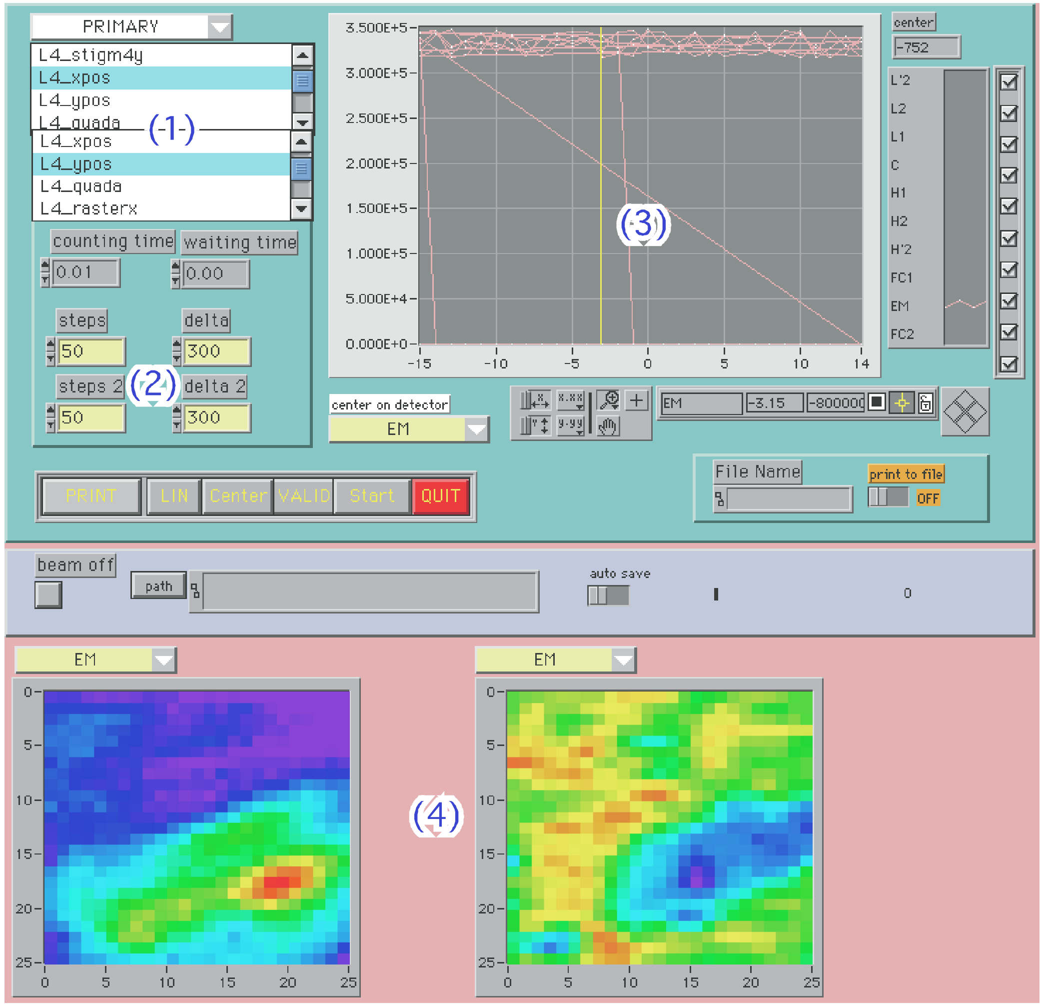


Figure 34: Interface of modified scan_param. The functions of parts are as follows; (1)parts to scan, (2)paramaters (3)line graph, (4)display image area.

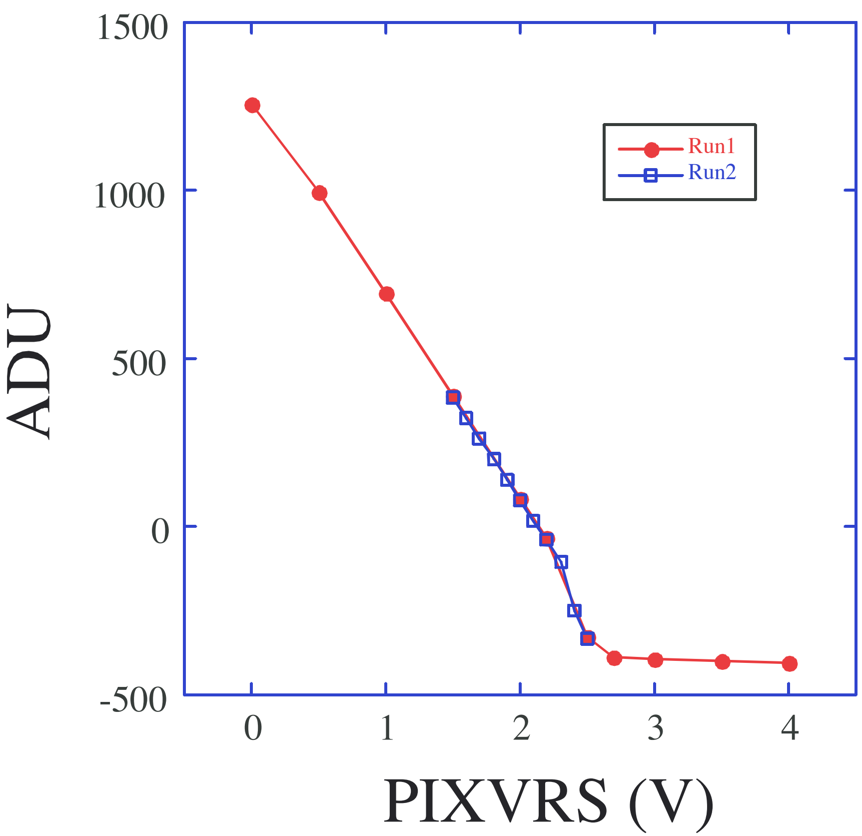


Figure 35: PIXVRS vs ADU

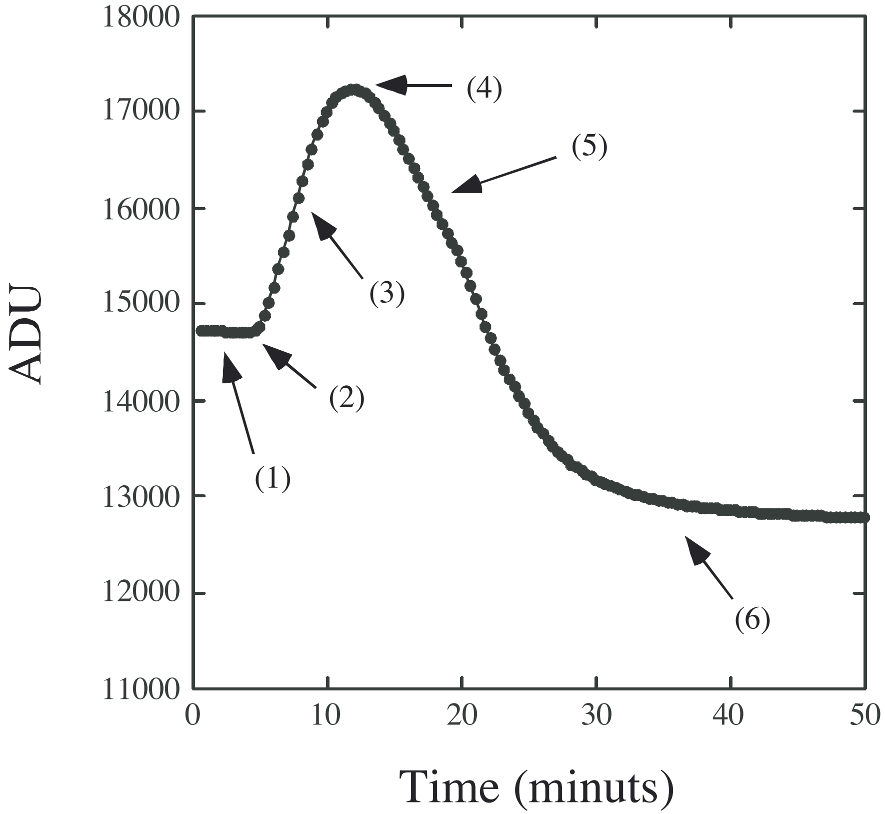


Figure 36: Cooling output characteristics of the conventional SCAPS system.

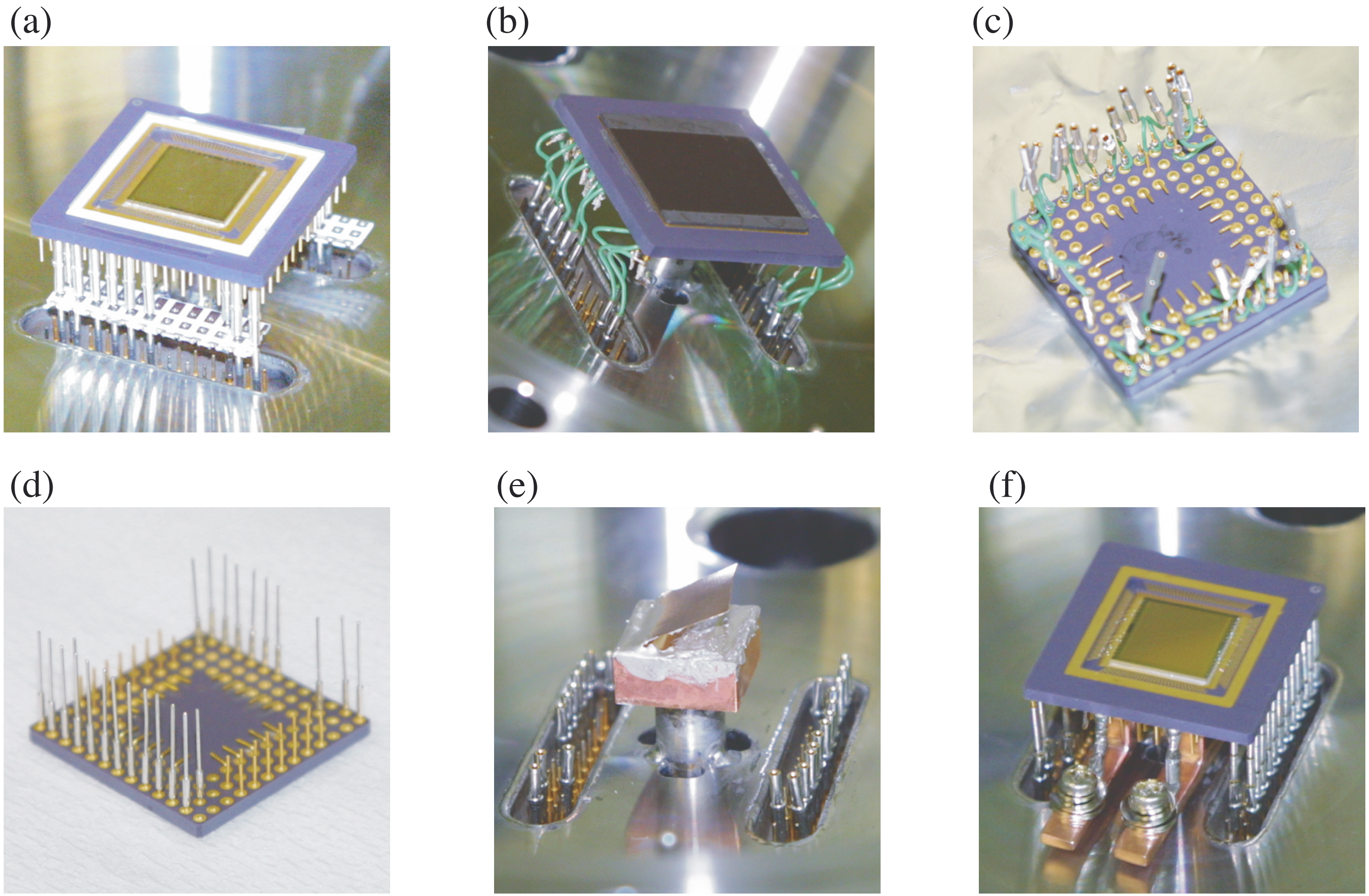


Figure 37: Several variation of SCAPS device for cooling. (a) Dotite bonds SCAPS and Cu cold finger. (b) Wrapping wire is used to privent SCAPS from unlatching. (c) Innermost pins are bent to fix the SCAPS and cold finger. (d)(e) Even if Cu contracts, it is made to be maintained at adhesion with SCAPS using single leaf spring fixed on cold finger with dotite. (f) Current version described in §2.4.4.

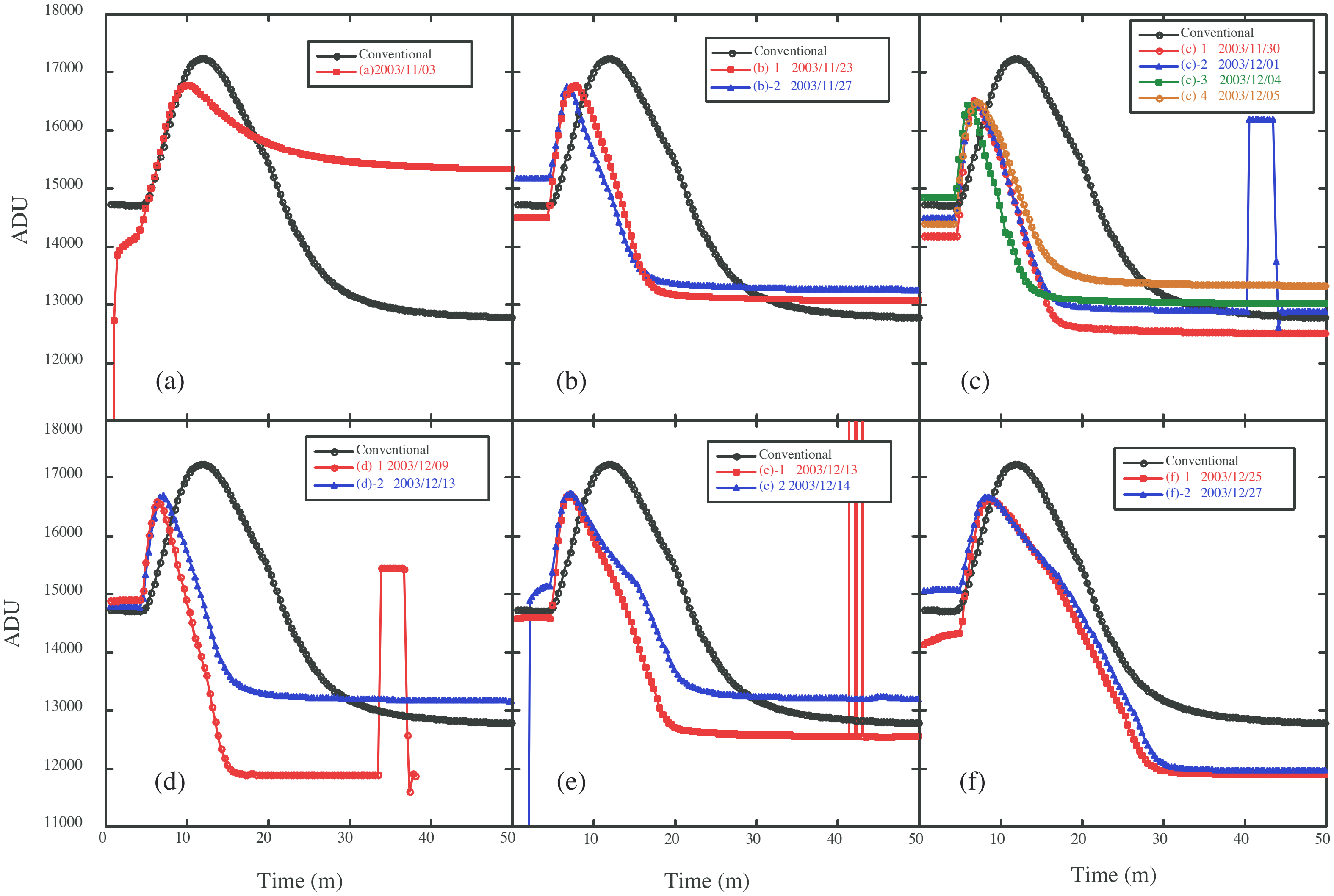


Figure 38: Output characteristics by cooling. (a)-(f) are corresponding to Figure 37.

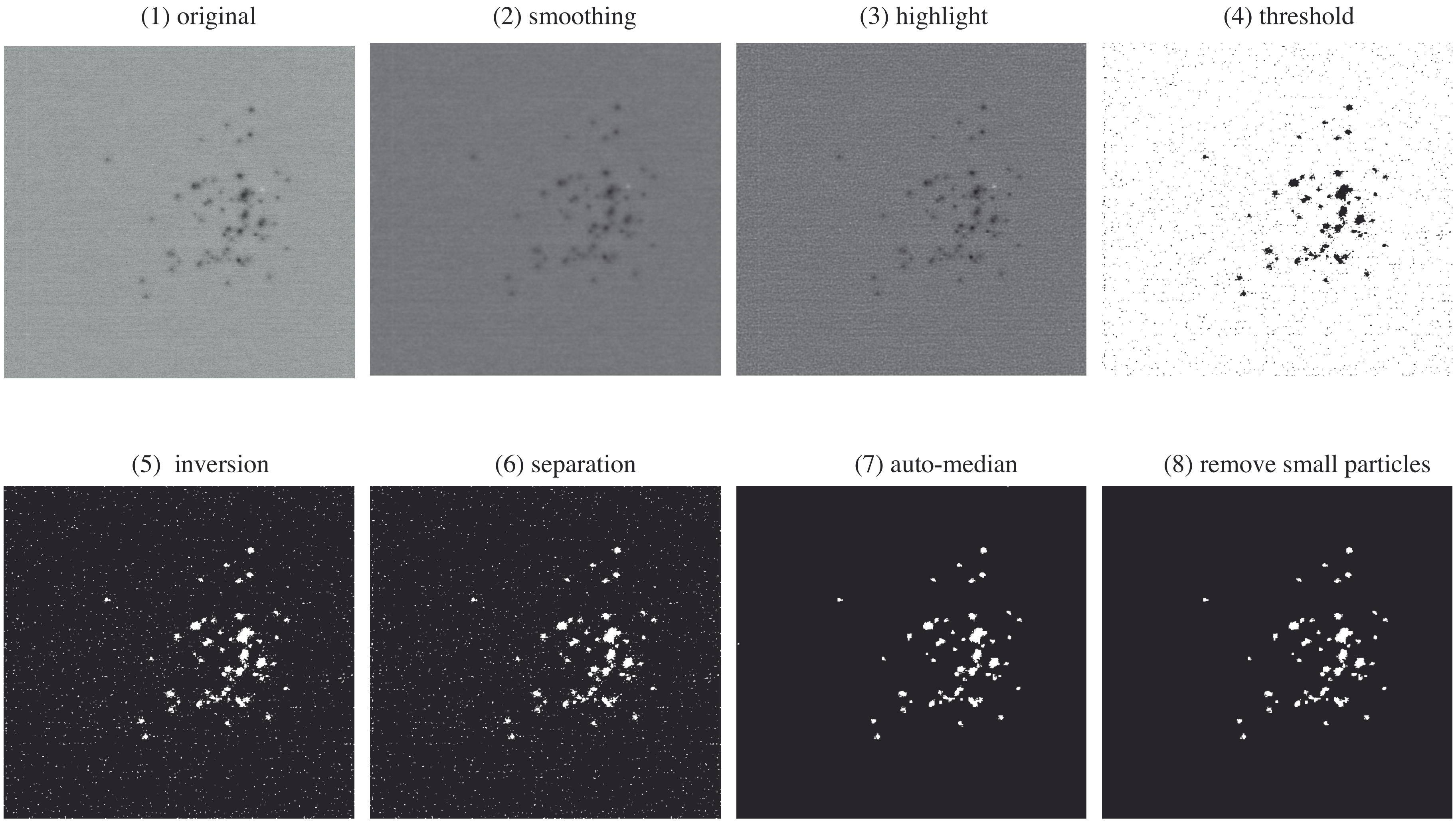


Figure 39: Sequence of image processing.

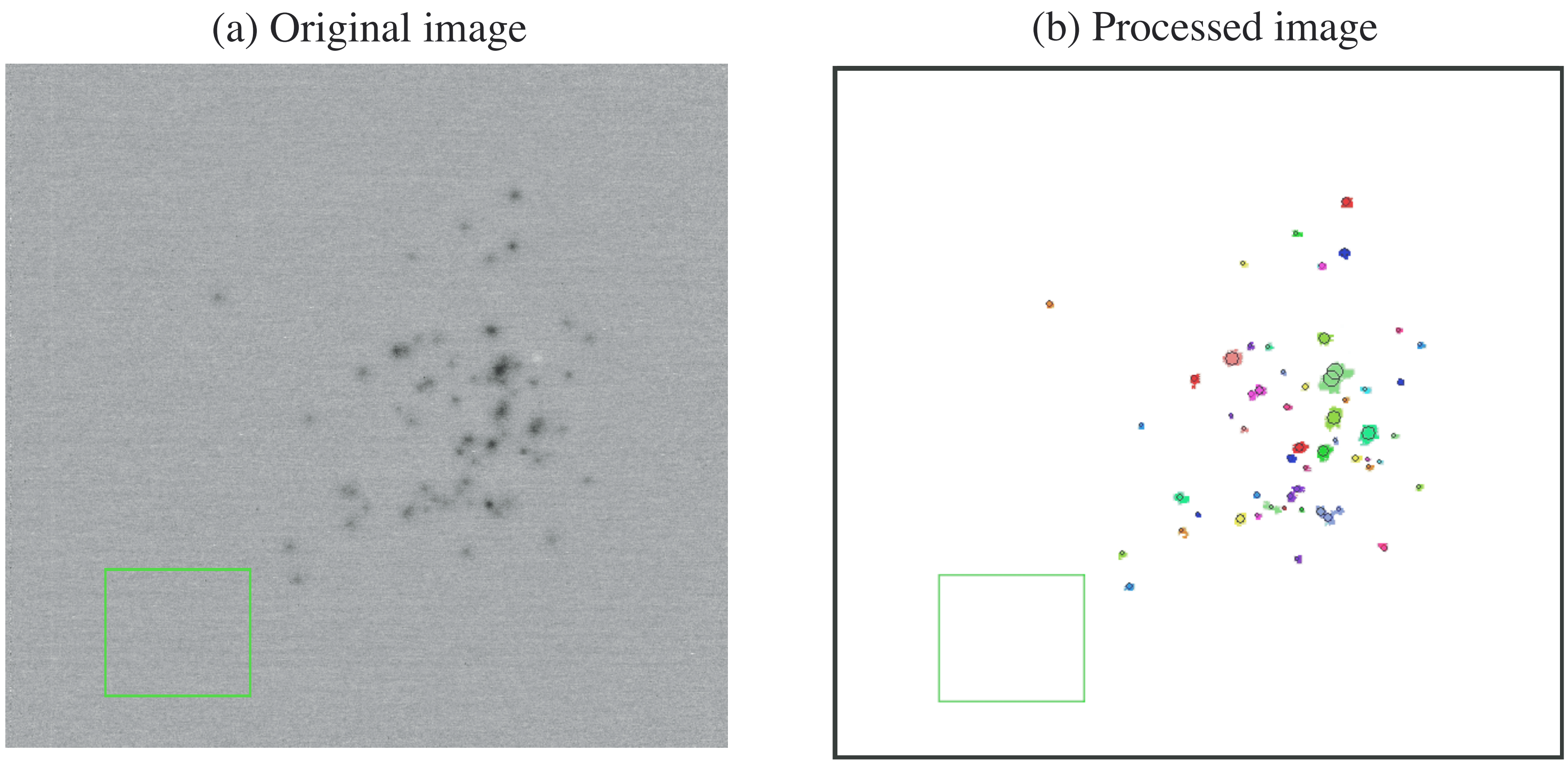


Figure 40: Images of single ion at MCP voltage Back: +16V, Front: -1100V. (a) is original image and (b) is processed image. Black pixels are signals of ion in (a). The region surrounded by green square is used to generate thresholds value in (b). The region of surrounded by green square is used to generate thresholds value.

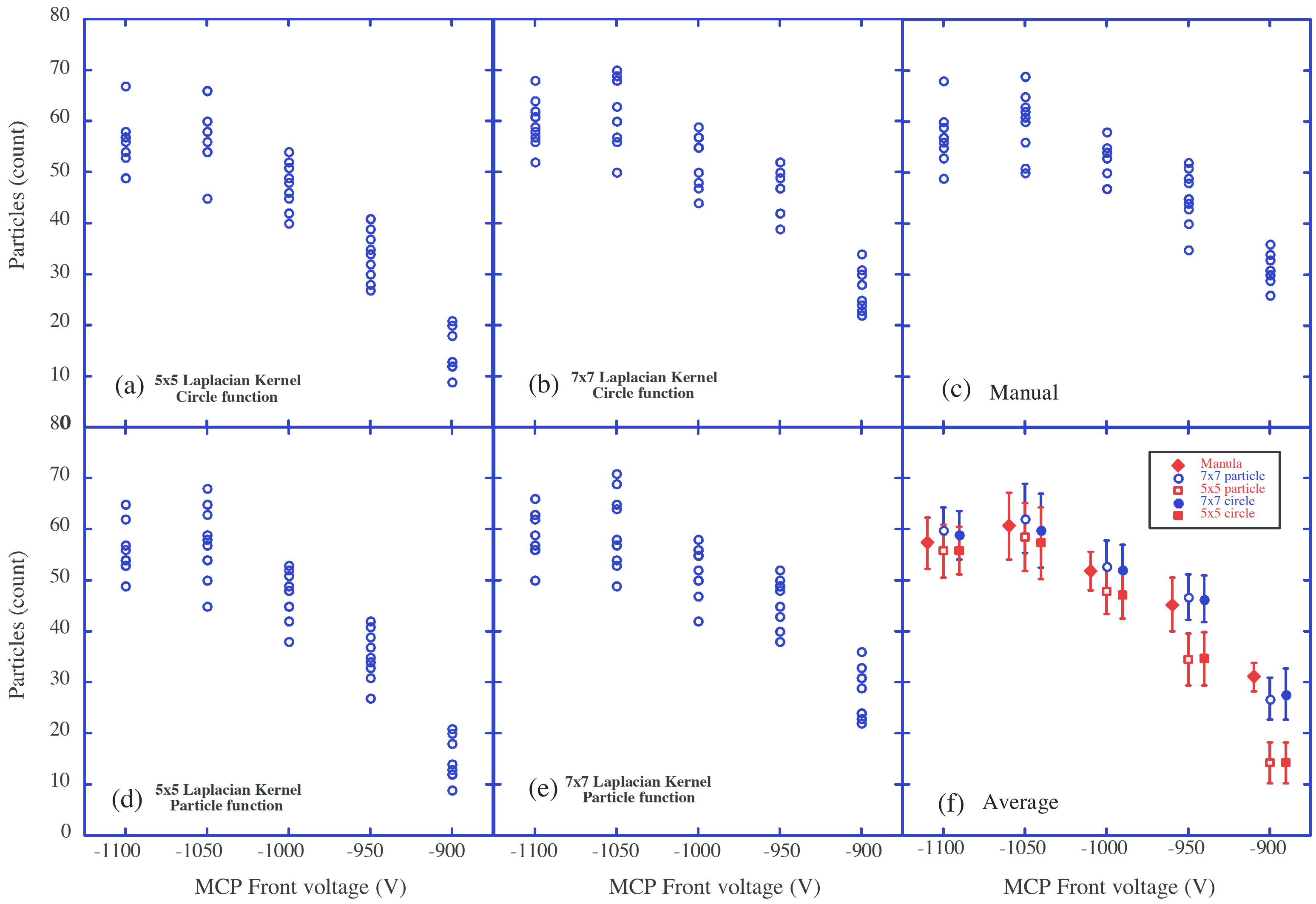


Figure 41: Result of automatic particle analysis. (a)Convoluted with 5x5 Laplacian kernal and analyzed using circle function. (b)Convoluted with 7x7 Laplacian kernal and analyzed using circle function. (c)Manual counting. (d)Convoluted with 5x5 Laplacian kernal and analyzed using particle function. (e)Convoluted with 7x7 Laplacian kernal and analyzed using particle function. (f)These values are averages of 10 times operation of (a) - (e). Error bar is standard deviation.

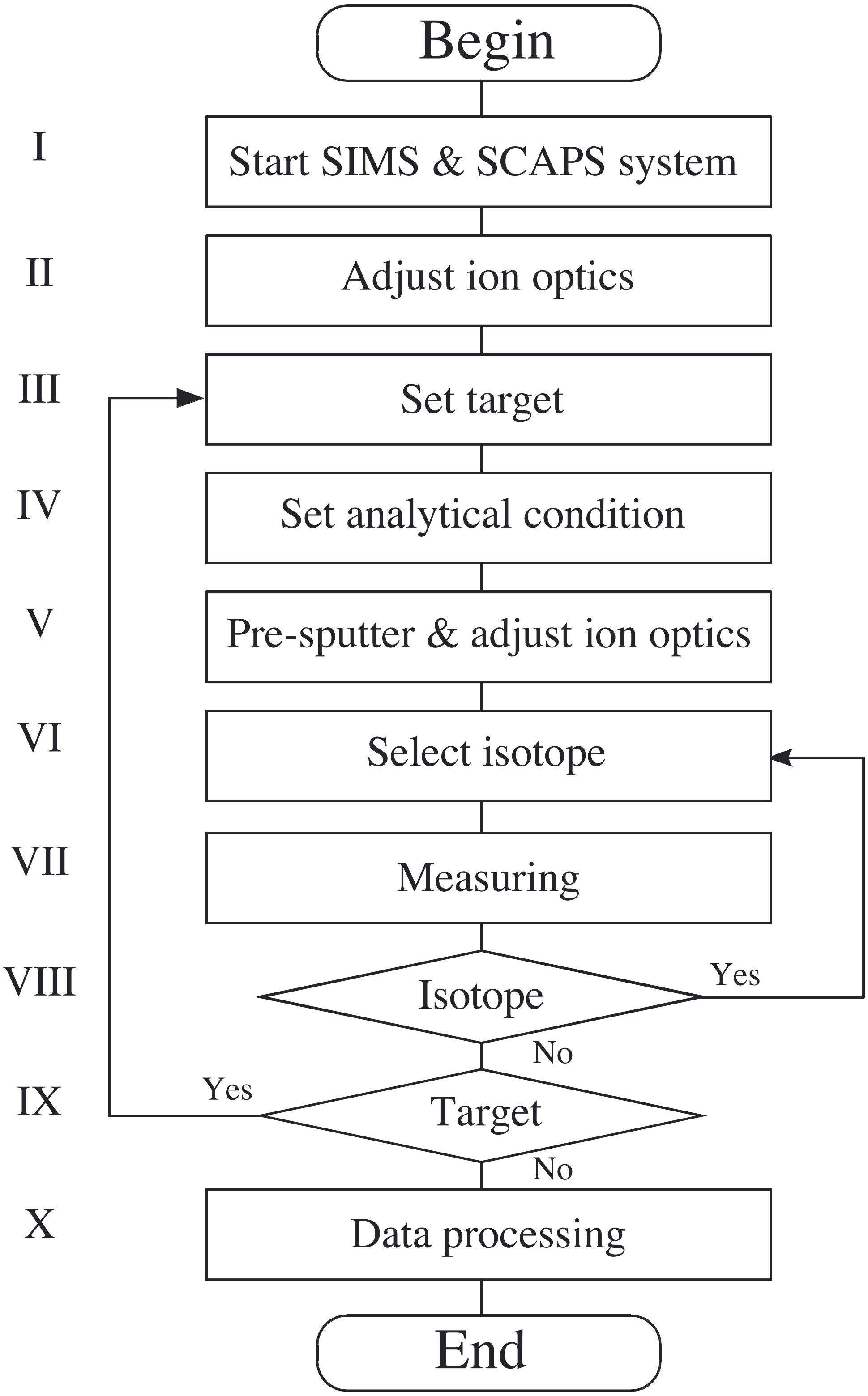


Figure 42: Schematic operational flowchart of isotope microscope.