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ORIGINAL RESEARCH ARTICLE

ON-ORBIT RESULTS OF PHOTOELECTRON CURRENT MEASUREMENT SYSTEM IN LOW EARTH ORBIT ON HORYU-IV SATELLITE

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ABSTRACT
On-orbit photoelectron current experiment is one of the missions carried out with the less resource available from a HORYU-IV satellite, for measuring the current from metallic and insulator surfaces from air mass zero (AMO) spectrum. This is with the view to determined photoelectron potential of materials widely used in spacecraft in space. HORYU-IV also known as Arc Event Generator and Investigator satellite (AEGIS) is among HORYU satellite series of Kyushu Institute of Technology, which was launched on February 17, 2016 as a piggy-back on-board H-IIA rocket. The measurement system consists of current-voltage amplifier circuits for Au, Kapton and Black Kapton samples with varying gains and other discrete components. We present the analysis of the telemetry data obtained after the launch; validate the effectiveness of the design and verification processes. The results show that the current measured from Black kapton sample surface had 1.80 nA and 2.70 nA, corresponds to 69.1º and 75.1º minimum and maximum elevation angles respectively. This paper described the on-orbit result of PEC and its verification through ground tests

1.0 Introduction

On-orbit photoelectron current measurement is very significant in the estimation of photoelectrons emission influence on spacecraft charging and therefore discharge phenomenon. This could provide basic information in predicting photoelectron potential on spacecraft and the electric properties of various materials irradiated by sunlight. Through this, most suitable materials could be selected during the spacecraft design phase.

Spacecraft operating in the sunlight cannot avoid one side exposing to the sun while the other side is in shadow, so it has to face the problem of surface charging caused by photoemission phenomenon (Jiang et al., 2015).

The photoelectron current as a consequence of photoelectric effect can cause spacecraft exposed to sunlight to develop a positive charge. This can be a major problem, as other parts of the spacecraft in shadow develop a negative charge from nearby plasma, and the imbalance can discharge through delicate electrical components (Lai, 2011).

Spacecraft surface charging can lead to arcing and a loss of electrical power generation capability of solar panel or even loss of a satellite (Mundari et al., 2011).

Spacecraft charging is a serious issue for safety of spacecraft operation. Therefore, thorough investigation of spacecraft charging at an early stage of satellite design is desirable to prevent the fatal anomaly in orbit. Charging properties, such as secondary electron yield, photoelectron emission yield and conductivity of spacecraft surface materials are the important parameters to predict charging in orbit (Ewang, 2017).

In order to overcome these anomalies, a voltage-current amplifier circuit was developed to measure photoelectron current in the orbit using the facility of HORYU-IV satellite.

HORYU-IV is a 30cm cubic satellite with an approximate mass of 10kg. HORYU-IV carries a high voltage photovoltaic solar array capable of generating a voltage up to 350V. Its main mission is to acquire an arc current waveform by an onboard oscilloscope and capture its image by a camera triggered by the oscilloscope (Cho et al., 2016).

In addition, PEC mission is one of the scientific experiments carried out by this satellite, located on its – Z panel. The satellite was successfully launched to an orbit of 575km altitude and 31^{o} inclination on February 17, 2016 by H-IIA rocket as a piggyback satellite with ASTRO-H (Hitomi) satellite.

All experimental testing was performed at the Laboratory of Spacecraft Environment Interaction Engineering (LaSEINE) in Kyushu Institute of Technology, Kitakyushu, Japan.

This paper presents on-orbit results of the photoelectron current measurement system on-board HORYU IV satellite.

2. Photoelectron Emission Current Definition

The electron emission by photon as a fundamental particle of light, is massless and has no electric charge, whereby free electrons are emitted. The current produced due to this process is called photoelectron current (Jph). This is expressed in Eqn. (1), while Eqn. (2) expresses the current from the sample surfaces. Eqn. (3) is the photo fluence; define as the ratio solar intensity per energy of the photon from sun light.

$$Jph = q \text{ x} \int_{\lambda_1}^{\lambda_2} F(\lambda) \text{x} Y(\lambda) d\lambda \quad (1)$$

$$I_{sample} = q_e \times S \times \int_{\lambda_1}^{\lambda_2} F(\lambda) \times Y(\lambda) d\lambda \quad (2)$$

$$F(\lambda) = Ir/W \quad (3)$$

2.1 On-orbit Photoelectron Current

This is defined as emitting electrons from the sunlit surface of a spacecraft (Muranaka et al., 2009). These photoelectrons are created when photons strike the spacecraft surface and impart enough energy to induce electrons emission from the spacecraft surface. Typical photoelectron energy is about a few electron-volts. The number of photoelectrons produced and their energies are largely dependent on spacecraft material properties and designs (Jose,2003). As a result of

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electrons emission due to photons strike, a current is produced, namely the photoelectron current, Jph.

2.2. Principle of Photoelectron Current On-orbit Measurement

Figure 1 shows the schematic of principle of on-orbit PEC measurement mission. This is based on the photoelectric effect whereby when the sun sensor measurements, provided by the AODS through ADC in serial peripheral interface (SPI) mode, shows that the incident sunlight on the -Z panel of the satellite is within the threshold of 16.5º. Then the Big Apple microcontroller subsystem of HORYU-IV closes the +24 V switch to bias the PEC grid electrode. The sun sensor allow energy carried in a photon from the sun light (UV), transmitted to an electron in the surface of Gold, kapton(R) polyimide and Black kapton (R) samples on PEC subsystem and mission starts. (Ewang 2017).

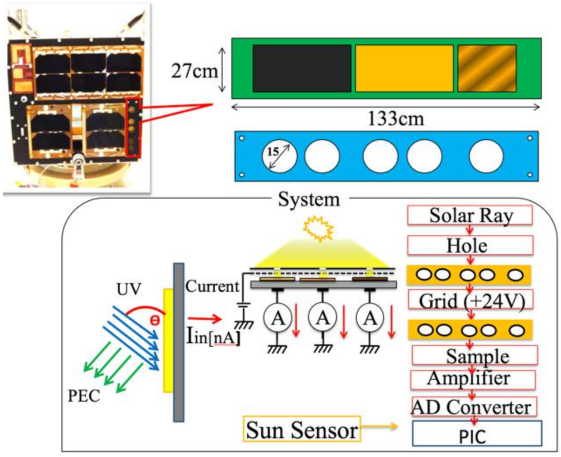

Fig. 1 Schematic of principle of on-orbit PEC measurement, (Ewang 2017)

The electron absorbs the photon's energy and dislodged from the surface of these materials. This thereby, creates a small electric current. The PEC measurement system, comprises of current-voltage amplifier circuit is used for the amplification of this current.

At the end of the mission, the microcontroller in Big Apple board receives data from PEC system, which are then written to its flash memory. The OBC reads the PEC data through flash memory prior to data transmission through UHF Yagi antenna to the ground station. (Ewang et al., 2017).

3. Materials and Methods

3.1 The Circuitry of Photoelectron Current System

Figure 2 shows the schematic of PEC circuit board. This is made of a current-voltage amplifier circuit that consist of two amplifiers; the LMC6001 ultra-low input operational and MCP6032SN operational amplifiers, with the capacitors, resistors, and others discrete components.

This circuit was designed to have three sub-circuits mounted on a single board for measurement of each sample (Gold, kapton(R) polyimide and Black kapton (R)) output current. Each material sample has its own dedicated circuit with gains of 1G, 3G and 1G, respectively. The circuit was designed with Easily Applicable Graphical Layout Editor (EAGLE) software and the components were located on the printed circuit board (PCB) as defined in the circuit diagram and then soldered.

The circuit has an Electrical Power system (EPS) connected to supply ±5V to DCDC converter which converts to ±5volts and +24volts levels. The ±5V is used to switch on the PEC circuit and +24V for generating of the required voltage for grid electrode. This +24V grid electrode is useful in the process of emitting the photoelectron current from the sample surfaces. The LMC6001is connected in the circuit to amplified the photoelectron current measured at the sample surface. This is connected to the input (Cin) and feedback (Cf) capacitors to maintained the required voltage level. The input current (Iin) is use to move the current from sample surface along the circuit over R1. A pull up resistor, 9.1 k in the circuit ensures that the signal was at a valid logic level.

At point V1 the produced voltage was negative. The MCP6032SN connected to it amplifiers the voltage, converts it to a positive value that could be read by microcontroller circuit of Big Apple subsystem of HORYU IV. The Big Apple serves as a memory via the PIC device on the Big Apple board for storage of PEC data. Interfaced between PEC subsystem with the electrical power system (EPS), altitude orbit and determination system (AODS) and on-board computer (OBC). At Vout, the waveform is obtained over the oscilloscope via AD converter; the data collected and analyzed using Eqns. (4) – (6), to obtained an equivalent input current for each sample. (Ewang, 2017).

$$V = -I_{in}R_1 \quad (4)$$

$$V_{out} = R_4R_1I_{in}/R_3 \quad (5)$$

$$I_{in} = Vout/R_1 \quad (6)$$

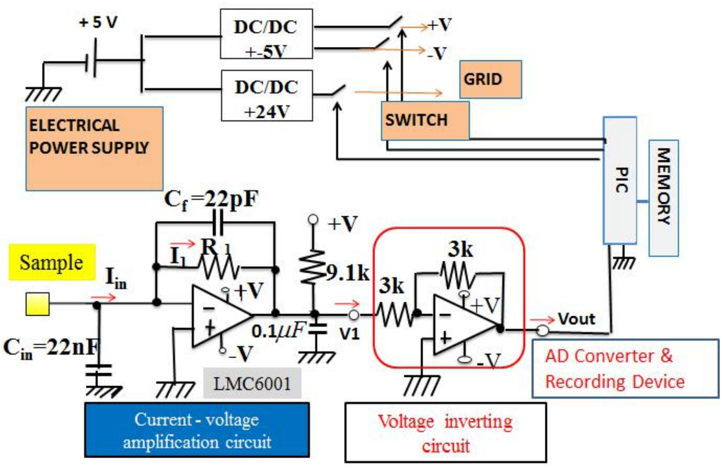

Fig. 2 Schematic circuit of PEC board

3.2. PEC Measurement System

Figure 3 depicts the schematic diagram of on-orbit PEC measurement system onboard HORYUIV satellite. The system comprises of the voltage-current amplifier printed circuit board (PCB), samples, +24 volts' grid electrode, holes and analog to digital converter (ADC).

The PEC PCB consists of a rectangular PCB with a length of 133mm and width of 27mm. The PCB is made of three dedicated circuit for each sample, mounted on one board. Each of this circuit is

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identified with 1GΩ, 3GΩ and 1GΩ for Gold, kapton ® and black Kapton samples respectively. The three samples are placed on the PCB front side and electronic components on the back side. (Ewang et al., 2017).

Dedicated holes for each sample were made on the insulator substrates and in the satellite structure. This is to allow photons strikes onto the different sample surfaces.

The area of each hole is based on the sample type. For the Au sample, there is one hole of 15mm diameter over the sample, whereas for Kapton® and black Kapton®, there are two holes of 15mm diameter over the sample to increase the sample area exposed to photons strikes and increase chances to generate and measure photoelectron current for these two samples.

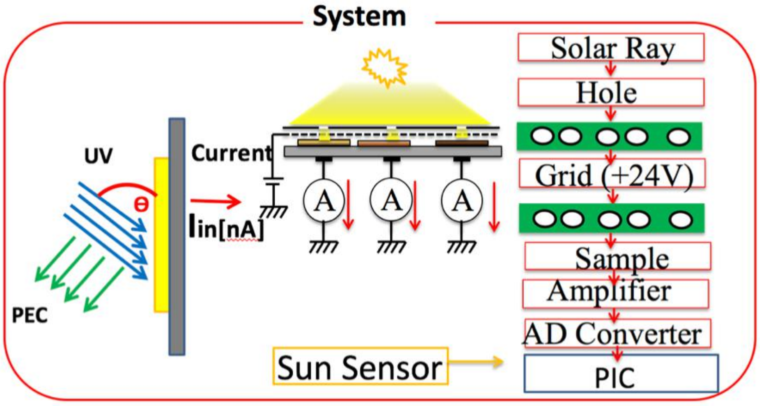

Fig. 3 Schematic of PEC measurement system

The biased mesh grid electrode at +24V with the same dimensions as the PCB is placed between the samples and the satellite panel. This grid was placed in between insulator substrates to prevent plasma sheath effect. These substrates protect the PCB from the effect of +24 V of grid electrode that could have interfere with the proper functioning of the circuit. And also prevent the heat effects to the electronic component on this board.

The Analog to Digital Converter (ADC) connected to the PEC circuit converts output signals to an equivalent digital number that is stored in the memory device, the Big Apple subsystem via the peripheral interface controller (PIC).

4. Experimentals

4.1 Ground Test Experiment

Experiments were performed to confirm the operation, verify the performance of the PEC system and to validate its accuracy. The experiments used a low earth orbit plasma chamber of dimension of diameter 1.0 m x length 1.2 m, pressure of1x 10-4 pa, temperature of 1.0 eV and pumping speed of 300 i/s. Located at the Laboratory for Spacecraft Environment Interaction Engineering (LaSEINE) of Kyushu of Kyushu Institute of Technology.

The Plasma was generated by electron cyclotron resonance (ECR) at 3.5 - 5 GHz. The xenon (Xe) gas was fed at a flow rate of 0.40 sccm controlled by a flow-meter. During the experiments, the gas pressure inside the chamber was maintained at 2.0x10-2 Pa. The chamber was evacuated by a rotary pump backed by turbo molecular pump connected in series that confirmed the ultimate vacuum level of 7.5x10-3 Pa. This chamber generates plasma density of 1011 ~1012 m-3(Ewang 2017)

Figure 4 shows the schematic diagram of PEC experimental set up in the LEO chamber. This consist of the PEC measurement system, Ozone light (GL-6Z: model), Oscilloscope (TBS1104), Voltage regulator (PSW-80-13-5 GW, INSTEK), Isolation transformer, Langmuir probe, Cylindrical cup, plasma source and DC source (Battery).

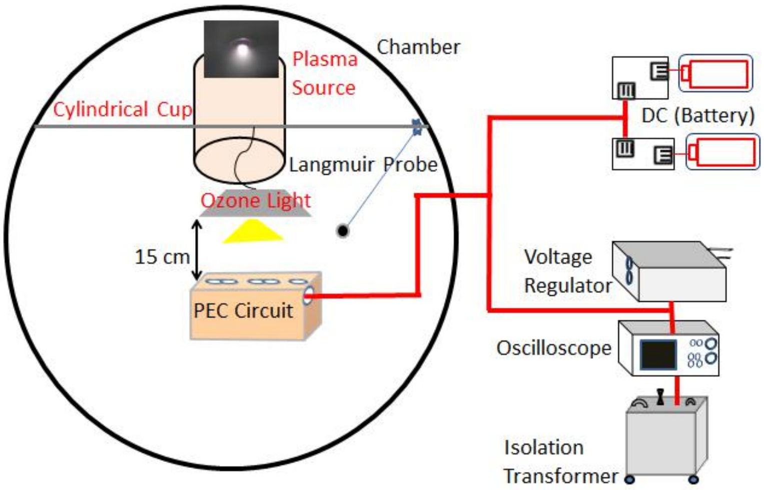

Fig. 4 Schematic diagram of PEC experiment in LEO chamber

The PEC system in an aluminum box of dimensions 178 cm x 178 cm x 71 cm shielded by kapton tape to prevent effect of plasma, has one input and output sources. The input consists of + 5 volts, - 5 volt and ground connected from the DC (battery) source. The output has Au, kapton (R) polyimide and Black Kapton samples source connected to the oscilloscope. The + 24 volts' line connected to voltage regulator to provides the required biased voltage to pull out more electron from samples surfaces. (Ewang et al., 2017).

All the electronic components were connected to a common ground and in series with the isolation transformer to suppress the effect AC noise. The box was placed 15 cm from the UV source. The cylindrical cup was to regulate the plasma density by changing its position in the chamber. And the Langmuir probe was to measure the plasma parameters in the chamber. The output waveform was observed over the oscilloscope; the data collected and analyzed.

4.2 In-orbit Experiment

The mission success criterion is in-orbit photoelectron current measurement from the metallic and insulator surfaces from AMO spectrum. HORYU-IV was launched aboard HII-A F30 at 17:45, February 17, 2016 (JST) from Tanegashima Space Centre. The satellite was inserted into an orbit of 575km altitude and 31° inclination. After the launched, PEC mission on-orbit experiments have been successfully performed from AMO spectrum; June 20, and July 08, 2016. The result of the experiment performed on June 20, 2016 has been published (Ewang et al., 2017).

Figure 5 shows the schematic diagram of PEC interface connections with others subsystem of HORYU IV satellite. The sequence of operation was such that when the PEC signal was turned on from Kyutech ground station, the OBC writes a command to the Big Apple flash memory. The microcontroller in the Big Apple board reads this command and closes a 5 V switch, provided by (EPS) power system. If the –Z panel sun sensor measurements, provided by AODS through ADC using serial peripheral interface connections, show that the incident sunlight measurement is at the acceptable threshold of 16.5° from the perpendicular to the surface. Big Apple microcontroller closes the +24V switch to bias the PEC grid electrode.

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This sun-sensor has square field of view (FOV) with half angle of 16.5 degree. The PEC mission starts.

After the mission ends, Big Apple microcontroller receives data from PEC system. Data received from PEC system are written to Big Apple flash memory. OBC reads the PEC data through Big Apple flash memory. PEC data are transmitted through UHF antenna to Kyutech's ground station. (Ewang, 2017).

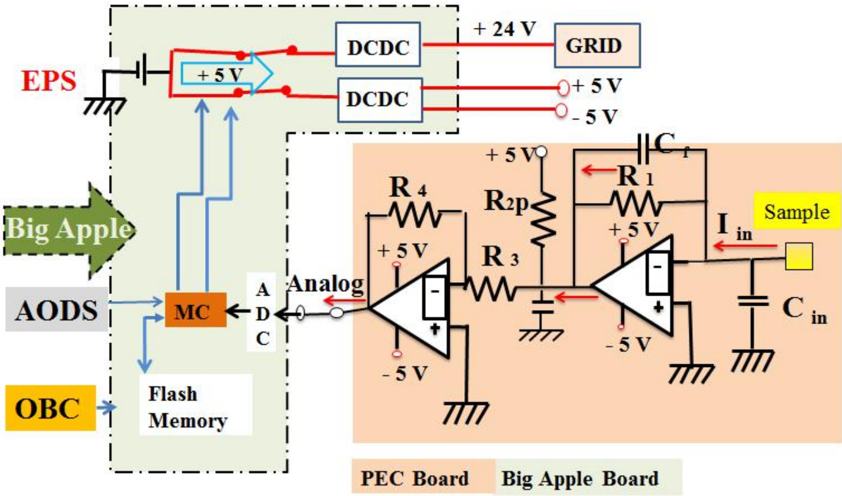

Fig. 5 Schematic diagram of PEC system interfaces (Ewang. 2017)

5. Results and Discussion

5.1 Ground Result

Figures 6(a) – (c) show the output current time profile for Gold, Kapton polyimide (R) and Black kapton (R) samples. These show that the PEC circuit was turned on at -0.5 second, +24 volts turned on at 0 second and mission was performed for 0.6 seconds.

Table 1 shows the measured maximum current values under UV only and Plasma and UV for each sample. The increase in current between the two signals is due to the plasma ions and electrons charge effect on the surface of these materials.

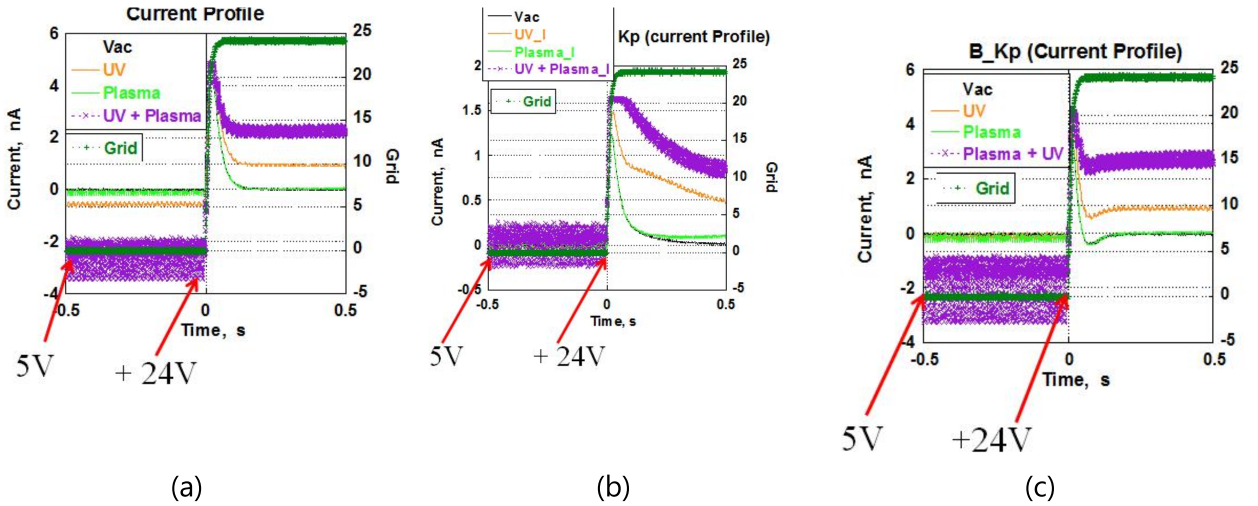

Fig. 6 Samples current profile. a) Gold; b) Kapton®; c) Black Kapton ® for ground data

Table 1 Measured current values for each sample

Sample	UV Only (nA)	Max. Plasma and UV (nA)
Gold	1.88	2.89
Kapton Polyimide ®	0.47	0.76
Black Kapton ®	0.88	2.60

5.2. On-orbit Results of PEC Mission

Figure 8 shows the PEC on-orbit result of July 08, 2016.The data were obtained on the orbit relative to the earth at (28.6016 ° E, 115.7390 °N) in China and (26.9462° E, 129.1254 ° N) in Philippine Sea respectively. Figure 7 shows the sun sensor signal to PEC mission of the data obtained. When the incident sunlight on the -Z panel of the satellite was at the threshold of 16.5 degree. Level1indicates when the signal was turned on at 249 seconds and level 2, turned off at 293 seconds.

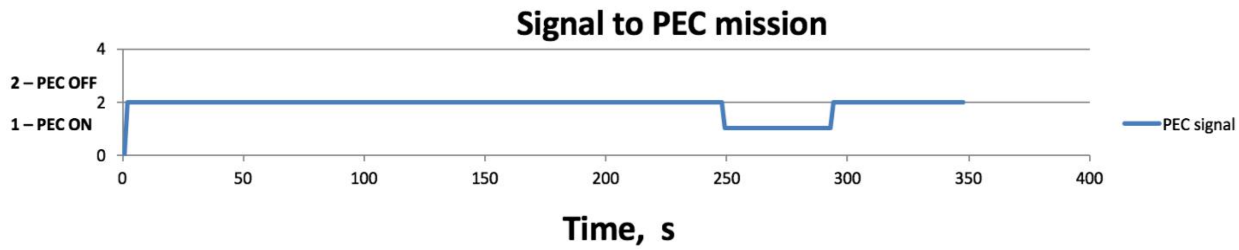

Fig. 7 Sun sensor Signal to PEC mission

Figure 8 (a)-(c) shows the current time profile for on-orbit current measured on the surface of the three samples. This shows that the PEC current was turned on at o second, when OBC writes a command to the Big Apple flash memory. The microcontroller in the Big Apple board reads this command and closes a 5 V switch, provided by (EPS) power system. When the sun sensors measurements, provided by the AODS through ADC in serial peripheral interface (SPI) mode, shows that the incident sunlight on the -Z panel of the satellite was within the threshold of 16.5°, then the Big Apple microcontroller closed the +24 V switch, biased the PEC grid electrode for 2 seconds and mission starts.

The Gold and Kapton ® polyimide current values went on saturation for 37.7 seconds. The Black Kapton (R) maintained a stable increased in the current values from 1.80 nA at 33.8 seconds to maximum value of 2.70 nA at 71.5 seconds. The Big Apple subsystem of HORYU IV, recorded these data for 37.7 seconds after that ellipse (EC) at value of 3.13 nA.

This shows that the current values were stable at 2.60 nA for 4 seconds between 34.1–35.7 seconds, with respect to minimum angle of elevation of 69.1°. Then changes up to 2.70 nA with respecct to maximum angle of elevation of 75.1°. These elevations were provided by the sun sensor via AODS subsystem of HORYU IV. This means that PEC can be measured from Black Kapton sample surface on HORYU IV satellite at minimum and maximum elevation angles 69.1° and 75.1° respectively.

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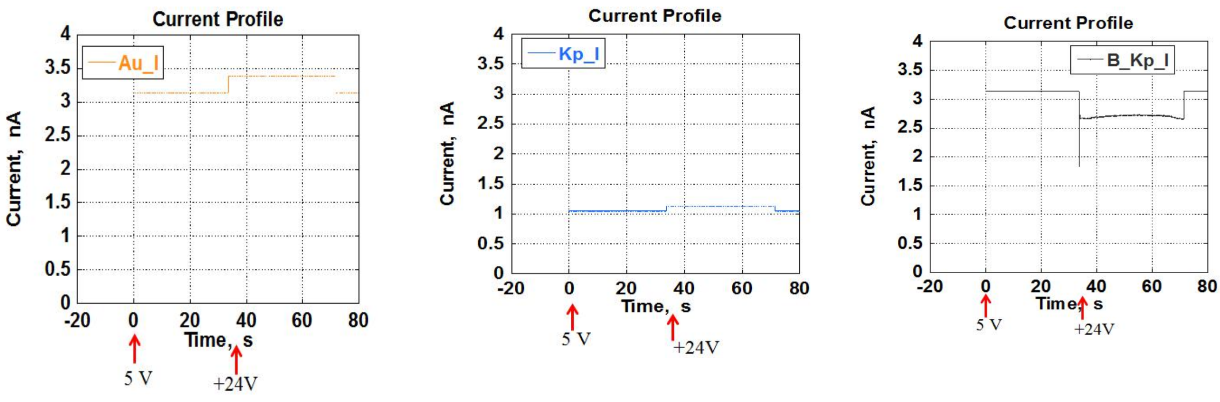
After 71.5s, there was no incident of sunlight, due to an exit sun from the threshold of the sun-sensor, then showing value of 3.13 nA. Table 2 indicates the on-orbit measured current with corresponding elevations with respect to time. This means that the on-orbit minimum and maximum current values of 1.80 and 2.70 nano-amperes was measured, this corresponds to minimum and maximum elevation angles of 69.1 and 75.1 degrees with respect to time of 33.8s and 71.5s respectively. Photoelectron current emitted from a surface is directly proportional to the light intensity (Leijtens et al., 2008) and the proportionality constant depends on the surface material of the object (Milton et al., 1996). Thus, at maximum elevation angle, more photoelectron current is emitted.

The incident angle is measured from the perpendicular to the surface to the sunlight vector. The elevation angle is measured from the parallel to the surface to the sunlight vector. Figure 9 illustrates the sensor with characteristic of a square field of view with half angle 16.5º. With: d1 = d2 = 16.5º; d3 = 21.2º, maximum incident angle. PEC mission is ON when the incident angle is less than sensor field of view (16.5º). This 16.5º corresponds to the period the incident sunlight on the surface of material was within the acceptable threshold from 33.8s 75.1 s.

Table 2: On-orbit current with respect to time

Time, s	Incident Angle (º)	Elevation Angle (º)	Orbit Current (nA)
33.8	20.9	69.1	1.80
71.5	14.9	75.1	2.70



(a) (b) (c)

Fig. 8: Samples current profile. a) Gold; b) Kapton®; c) Black Kapton® for on-orbit dat

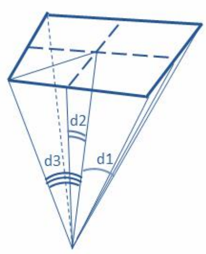


Fig. 9: Sensor field of view

In this study, photoelectron current for Black kapton ® polyimide was measured in orbit. Previously, photoelectron current density in orbit was determine for Black Kapton® polyimide sample (Ewang et al., 2017). Looking at these results, it is observing that the photoelectron current measured is within the range as in (Ewang et al., 2017). Thus, serves as a confirmation to this study.

6. Conclusion

On-orbit result of photoelectron current measurement system in Low Earth Orbit (LEO) on HORYU-IV Satellite was implemented. This was with a view of measuring photoelectron on-orbit from the sample surfaces. PEC measurement system demonstrated its capability to measure photoelectron current in the order of nano-Ampere in LEO using a biased grid electrode.

Photoelectron current was successful measured on orbit from Black Kapton sample surface at 1.80 nA and 2.70 nA with minimum and maximum angles of elevations of 69.1^{o} and 75.1^{o} respectively.

Thus, indicates that at higher elevation angle with higher intensity from the sun light, there was more photoelectron current from the sample surface.

This indicates that the +24 volts' grid biased electrode was working both on ground and in space.

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