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High-resolution detection of 100 keV electrons using avalanche photodiodes

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ABSTRACT

With two electron beam sources, we have tested two new Hamamatsu [Hamamatsu Photonics K.K., Shizuoka, Japan ⟨http://www.hamamatsu.com/⟩] avalanche photodiodes (APDs) of spl 3988 and spl 6098 to detect electron beams up to 100 keV. Though our previous results showed the effectiveness and the advantage of an APD to measure 2–40 keV electrons, its upper limit was not high enough to detect so-called medium-energy electrons. In addition to the limitation of its detectable range, the response at different energies was also not linear. These newly developed APDs, which have thicker depletion-layers, provide full coverage of this missing range along with a good linearity. The depletion-layer thickness was increased to 140 μm for both APDs, the dead-layer of spl 3988 became 10 times thicker than that of spl 6098. The thin-surface dead-layer and thick depletion-layer of spl 6098 allows the detection of electrons from 3 keV up to 100 keV with a good linearity and with an excellent energy resolution of 4 keV at 100-keV electrons. The wide dynamic range from 3 keV to 100 keV of those APDs will increase their appeal in detecting electrons for space plasma research.

1. Introduction

In the field of space plasma physics, electrons in the energy range between several keV and 100 keV is called medium-energy electrons [1,2]. Since the medium-energy range borders two techniques of lower-energy and higher-energy, it is difficult to detect electrons in that energy range accurately and reliably. Moreover, this range represents a thermal to non-thermal transition range of electron energy spectra from the perspective of space plasma physics [3–5]. Therefore, a new method to detect medium-energy electrons is strongly desired for future exploration missions to the sun, geospace, and other planets.

In measuring medium-energy electrons, avalanche photodiode (APD) has attractive properties such as a fast response, a high energy resolution, and a low detectable limit. Those properties are derived from the avalanche multiplication of signal carriers inside the avalanche-layer where there is an extremely strong electric field. We succeeded in detecting electrons from 2 keV to 40 keV by using Hamamatsu spl 3989 [6–8] with a good energy resolution. However, some practical problems remained, such as insufficient dynamic range, linearity, temperature dependence of the response, expansion of the detectable area, and torelance for the radiation dose. In this paper, we focused on two of these key problems, the dynamic range and the linearity. The coverage over the higher-energy level measuring up to about 100 keV is important to achieve an on-board cross calibration with conventional silicon Solid-State detectors (SSDs) [9,10] due to the low energy resolution of SSDs at 100-keV range. SSDs have been used for electrons over several tens of keV in detecting energetic particles of space plasmas. As discussed further in our former papers [7,8], we demonstrated that two properties of APDs were important for the dynamic energy range to be determined. The lower limit of detection is determined by the thickness of the dead-layer, and the upper limit of detection is determined by the thickness of the depletion-layer. Our former result by spl 3989 [8] was up to 40 keV at best because of the limitation of the depletion-layer thickness. The Hamamatsu spl 3988 and spl 6089 have 140 μm depletion-layers as summarized in Table 1. This thickness is about five times as thick as that of the spl 3989. From our numerical calculations in Ref. [8], 140 μm of depletion-layer corresponds well up to 150 keV. However, there are some concerns about linearity when APDs are used for electrons with higher-energy than 50 keV. In the first place, nonlinear response

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Table 1
Parameters for APDs mentioned in this paper

Type	Z7966 [7]	spl 3989 [8]	spl 3988	spl 6098
No.	20	1	126	1, 2
Dead-layer thickness (μm)	~0.3	~0.1	~2	~0.2
Depletion-layer thickness (μm)	10	30	140	140

can be caused by the signal current density produced in APDs. The voltage drop across load resistance, or the space charge by the carriers in the avalanche-layer, can weaken that electric field and reduce the multiplication rate itself. Local heating is also a probable cause. This will end in the saturation of response linearity [11]. Secondly, the variation of internal electric field around the avalanche-layer can de-homogenize the electric field in the deeper part of the APD where higher-energy electrons could reach. If the avalanche-layer has a finite thickness, electron–hole pairs created in the layer travel only short paths in the high electric field of that avalanche-layer. This mechanism can also cause the lowering of the output charges and the saturation of the linearity curve [8]. Finally, spl 3989 indicated an internal structure of electric field at the depth of 1 μm [8], which caused a bend of the response linearity curve in case of spl 3989. We aimed to experimentally demonstrate the usefulness of thick depleted APDs by detecting 100-keV electrons using two electron beams. We used a newly developed electron beam source facility in Rikkyo university to produce those 100-keV range electrons. As mentioned above, we prepared two thick APDs of the spl 3988 and the spl 6098. The spl 3988 has a dead-layer of several microns, but the spl 6098 has a tenth of that dead-layer. Since the depletion-layer thickness is the same for both spl 3988 and spl 6098, we could experimentally check the impact of the dead-layer thickness on the lower limit of detection energy.

2. Measurement systems and setups

2.1. Remarks on the APDs in this paper

All APDs referenced in this paper along with important specifications are summarized in Table 1. Both spl 3988 and spl 6098 have the *reach-through* type structure [12–16]. No. 1 and No. 2 represent lot numbers for spl 6098, which were produced from the same wafer. These devices need only about 400 V for full depletion due to its narrow avalanche-layer, which is one of the advantages of the reach-through structure. In order to minimize the energy resolution against 20-keV range electrons, we chose the bias voltages of 390 V for spl 6098 No. 1, 370 V for spl 6098 No. 2, and 370 V for spl 3988 No. 126. Another important feature is that these APDs are full depletion type, allowing them to be put in front of the other stack of SSDs or APDs in order to measure ΔE of penetrating particles. We define the *foreside* as the side with the p-type layer and the *backside* as the n-type side with an avalanche-layer. All experiments in this paper are done by foreside injection.

2.2. Electron beams

For our measurements, we used two electron beam facilities. One is the facility in the Institute of Space and Astronautical Science in Japan Aerospace Exploration Agency (ISAS/JAXA), and the other is the facility in Rikkyo university. We distinguish them with the terms "ISAS beam" and "Rikkyo beam". Fig. 1 shows a schematic configuration of the experimental system in ISAS beam for measurements of electrons up to 20 keV. The system of an electron gun was insulated by a pipe made of ceramics from the chamber body. The potential from −1 kV to −20 kV was applied to that electron source, so that electrons can be accelerated up to the corresponding energy through the pipe. Thirteen circular electrodes were equally spaced and connected by resistors inside the pipe in order to make an uniform and linear electric field. The beam was directly measured by APDs. Two pairs of charge-sensitive pre-amplifiers and shaping amplifiers were connected just behind two devices inside the chamber. This allows us to calibrate two APDs simultaneously by using a linear motion manipulator. These amplifiers were populated on a substrate. In the charge sensitive pre-amplifier, 1 pF capacitor and 1 GΩ resistance were used for a negative feedback of the operational amplifier. The shaping time constant in the shaping amplifier was set to 1.5 μs. Shaped pulses were fed to set outside the vacuum chamber and analyzed by a pulse height analyzer. Two slits with a diameter of 2.5 mm were set about 10 mm above the APD surface. The APD surface was uniformly irradiated by the electron beam passing through that slit. The temperature of APDs was measured by a packaged IC temperature transducer of Analog Device AD590 [17] with a proper voltage supply from the atmosphere side. AD590 was mounted on the APD board separated from the amplifier board.

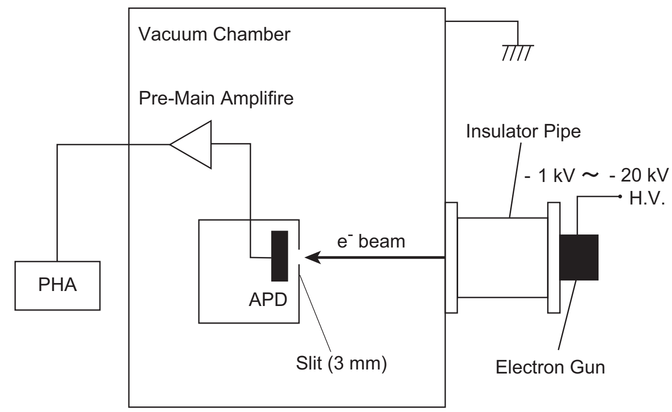

Fig. 1. A frame format of electron measurement system for APDs. PHA in the figure is an abbreviation of the Pulse Height Analyzer.

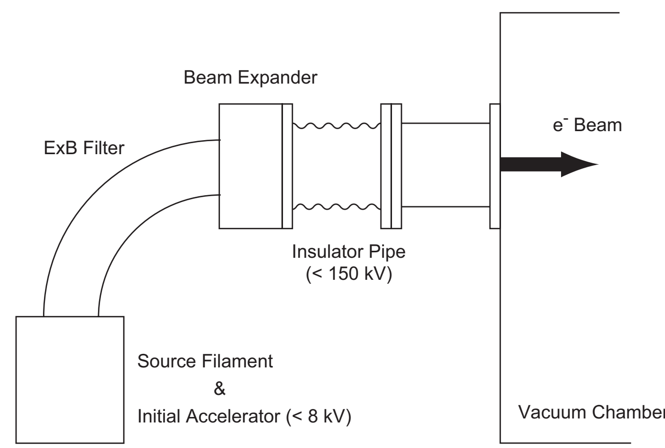

Fig. 2. A simplified diagram of electron beam source in Rikkyo university.

Fig. 2 shows a schematic view of the electron beam source in the Rikkyo beam. Thermions from the source filament were extracted and accelerated in the initial accelerator up to 8 keV. That initial acceleration voltage determines the minimum energy