Novel Solid-State Devices as Timing Detectors for Ion Time-Of-Flight Measurements.

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Abstract: This study reports on the performance of Avalanche Photodiode (APD) and Multi-Pixel Photon Counter (MPPC) as a timing detector for ion Time-of-Flight (TOF) mass spectroscopy. We found that the fast signal carrier speed in a reach-through type APD enables an extremely short timescale response with a mass or energy independent <2 ns rise time for <200 keV ions (1-40 AMU) under proper bias voltage operations. When combined with a Microchannel Plate (MCP) to detect start electron signals from an ultra-thin carbon foil, the APD comprises a novel TOF system that successfully operates with a <0.8 ns intrinsic timing resolution even using commercial off-the-shelf constant-fraction discriminators. Thin dead-layer MPPCs are also tested for the capability to directly count secondary electrons to replace the MCPs, and ~keV electrons were detectable. By replacing conventional total-energy detectors and secondary electron detectors in the TOF-E system, APDs and/or MPPCs offer a significant power and mass savings or an anti-coincidence background rejection capability in future space instrumentation.

Introduction: In the space plasma instrumentation, the speed, energy per charge (E/Q), and total E of the incident ions are separately measured and thus their mass (M), E, and charge state (Q) can be uniquely determined [1-3]. Commonly, the TOF section typically employs two Microchannel Plates (MCPs) that measure the signals generated by secondary electrons produced as ions incident on the sensor interact with a thin carbon foil (start signal) and a detector (stop signal). The timing difference between the start and stop signals measured by these MCPs is used to determine the speed of these ions. The total E of the ions is measured by a solid-state detector (SSD) located at the end of the flight path, utilizing a proportional response to the ionization energy loss in the detector. If one could use SSD signals for simultaneous energy and timing analysis, the electrodes and the MCP for stop electron timing signals can be eliminated and a simplified instrument with significant power and mass savings could be possible. In reality, the signal rise time from conventional SSDs is too slow to use in start/stop timing due to the un-saturated slow drift mobility of electrons and holes in silicon (<~10^6 cm/s for full-depletion configurations [4]). The typical response time of traditional SSDs is 10-100 ns [5-7], which is far too long for timing analyses in a TOF-based ion spectrometer (e.g. for space plasmas, this ideally requires <1 ns timing resolution). This study presents a new approach to TOF-based mass spectroscopy that utilizes solid-state APDs and MPPCs as the timing detector for primary ions and secondary electron, respectively. APDs and MPPCs operate with a stronger electric field than non-avalanching silicon SSDs: At a nearly saturating level (~10^7 V/cm) for silicon devices, the mobility of carriers in these detectors is expected to be ~100 times faster than those in the full-depleted active layer of SSDs. However, (1) the timing profile of APD signals and directly initiated by ions, and (2) the capability of MPPCs as a electron counter are not well understood.

Methodology (APD): We study the response of a reach-through type APD with a 145 um depletion layer and a 15 mm^2 active area [8] applied in a TOF system. Ions pass through the inlet slit to the APD, and create secondary electrons in an ultra-thin carbon foil. These secondary electrons, created at both the front and back surfaces, are deflected onto a circular Chevron MCP detector placed below the foil. A ring electrode is kept at an optimized voltage (~-100 V) to minimize the radial dispersion of secondary electrons. The arrival time of these secondary electrons were used as the start signal of the TOF coincidence window in the system. The stop signals from the APD are directly induced by incident ions and fed into the fast pre-amplifier of our TOF measurement system. The APD is biased at +450 V unless otherwise indicated in the text, and operated at room temperature (20 °C).

Key Results (APD): Figure 1 shows a summary of TOF spectra for several ion species having 100 keV total energy collected using the MCP-APD TOF system. From this figure, it is clear that the proposed TOF method provides an excellent TOF mass resolution which is capable of separating the H_2O and Ne (AMU 18 and 20) peaks at the ~3% level. Figure 2 summarizes the TOF results for all investigated ion species with several incident energies (30, 50, 100, 150, and 200 keV) as a function of ion M/Q. Solid curves indicate theoretical values of the ion flight time. These reasonable results thereby validates the functionality of this TOF mass spectrometry concept. Further detailed analysis for the APD timing resolution will be given in the presentation. By averaging all data points for fast ions >2x10^6 m/s, where the carbon foil time straggling is negligible, we estimate that the intrinsic TOF resolution of the MCP-APD TOF system is 780 ps.

Methodology (MPPC): As a secondary electron source, we used one-stage MCP for the simplicity of the set up and the capability to produce a large number of secondary electrons within a short time window. The particles injecting into the single stage MCP is converted to 100 to 1000 secondary electrons. These electrons are focused into a tiny MPPC active area through three electrodes. The MCP mount can be floated to accelerate the electrons up to 5 keV. The simulated electron travel time is 16 ns with a 0.5 ns dispersion. Assuming that one avalanche of the electron charge cloud is produced in one MCP pore ~1 um in diameter), most of the electrons will be detected within a response time of SiPM to produce significantly stronger signals than 1 p.e. signal. During this experiment, we used UV lamp to stimulate the MCP secondary electrons. The applied MPPC is a UV sensitive type with a 3x3 mm active surface comprised with 50x50 um pixels.The SiPM signals are amplified by a gain of 30, and directly counted by a universal counter.

Key Results (MPPC): Figure 3 shows the MPPC count rate as a function of the threshold level on the counter under various conditions. If we bias the MCP with 1300V, even if the UV lamp is turned off, the MPPC starts counting the electrons corresponding to MCP background counts. These MCP background count profile is totally different in their pulse height compared to the intrinsic MPPC background counts, because the number of MCP secondary electrons contributes to trigger avalanches in many pixels of MPPC. After the UV lamp is turned on, the count rate went high only for the large pulse height component in the count rate profile. This result clearly shows that these counts were produced by the secondary electrons originated in the MCPs, and thus the SiPM can count ~keV electrons. The MPPC intrinsic dark counts could be discriminated from ~3 p.e. threshold level.

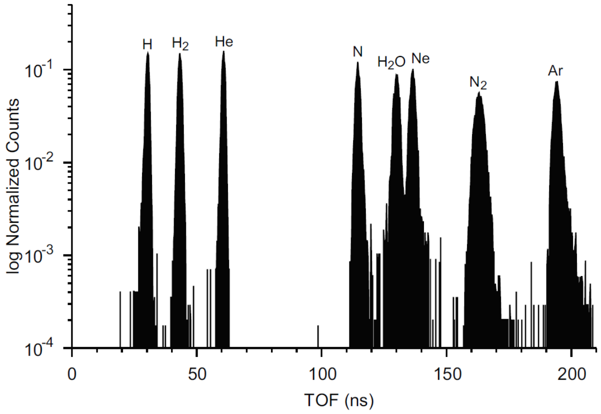

Figure 1: TOF spectra on a logarithmic scale for different ion species at 100 keV total energy obtained by the combination of MCP (Start signal) and APD (Stop signal) measurements. The accumulated counts in each ADC bin are normalized by the total count per each measurement, summed for all species. The foot of the peak prominent around the H_2O spectrum comprises contamination counts from the beam line structure by sputtering (Reproduced from Ref [8]).

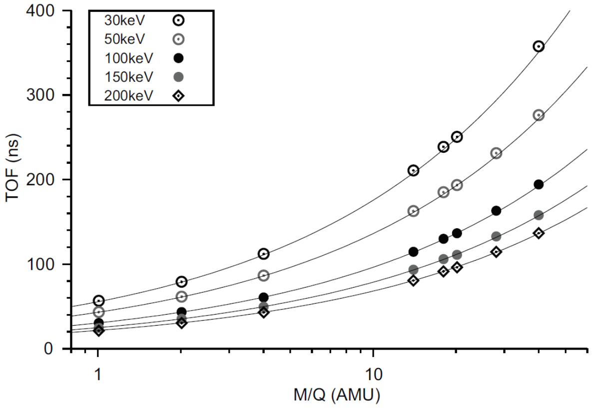

Figure 2: TOF curves as a function of ion mass per charge obtained by the combination of MCP (Start signal) and APD (Stop signal) measurements for 30, 50, 100, 150, and 200 keV ions of various species. Theoretical TOF curves based on a 13.3 cm flight path are shown for each energy (Reproduced from Ref [8]).

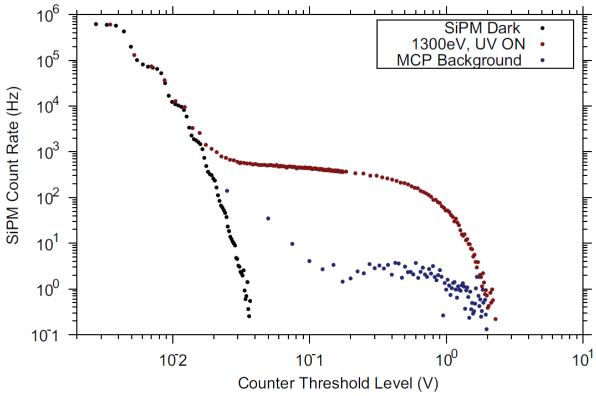

Figure 3: MPPC count rate profile as a function of different threshold levels on the counter. MPPC is biased at 66 V under a temperature of 19 °C in the vacuum chamber. Secondary electron signals are clearly distinguishable from MPPC dark counts.

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