Key elements of a low voltage, ultracompact plasma spectrometer

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Abstract Taking advantage of technological developments in wafer-scale processing over the past two decades, such as deep etching, 3-D chip stacking, and double-sided lithography, we have designed and fabricated the key elements of an ultracompact (1.5 cm)³ plasma spectrometer that requires only low-voltage power supplies, has no microchannel plates, and has a high aperture area to instrument volume ratio. The initial design of the instrument targets the measurement of charged particles in the 3–20 keV range with a highly directional field of view and a 100% duty cycle; i.e., the entire energy range is continuously measured. In addition to reducing mass, size, and voltage requirements, the new design will affect the manufacturing process of plasma spectrometers, enabling large quantities of identical instruments to be manufactured at low individual unit cost. Such a plasma spectrometer is ideal for heliophysics plasma investigations, particularly for small satellite and multispacecraft missions. Two key elements of the instrument have been fabricated: the collimator and the energy analyzer. An initial collimator transparency of 20% with 3° × 3° angular resolution was achieved. The targeted 40% collimator transparency appears readily achievable. The targeted energy analyzer scaling factor of 1875 was achieved; i.e., 20 keV electrons were selected for only a 10.7 V bias voltage in the energy analyzer.

1. Introduction

Beginning with single spacecraft and progressing to recent multispacecraft missions, exploration of near-Earth space has increasingly focused on understanding the energy flow and coupling between different spatial regions through simultaneous measurements of essential plasma parameters, e.g., magnetic field, electric field, density, and temperature, over the relevant spatial length scales. The International Solar Terrestrial Physics program’s Wind, Polar, and Geotail missions [Desch et al., 1997; Pulkkinen et al., 1997] and the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission [Angelopoulos, 2008] provided new insights and global perspectives on the flow of energy from the solar wind through the magnetosphere. Though highly successful, those missions were, and continue to be, limited by rare conjunctions and sampling of only one place in each region of the magnetosphere and upstream solar wind. The recently launched Magnetospheric Multiscale (MMS) mission has much smaller separations, down to 10 km, and the spacecraft fly in an approximately tetrahedral configuration (as did Cluster [Escoubet et al., 2001]), enabling direct calculations of the curl of the magnetic field, that is, the current density and other 3-D spatial differential quantities. Such spatially resolved measurements are critical for understanding the electrodynamics of different parts of the magnetosphere.

The next step in multispacecraft missions is to go well beyond missions consisting of a handful of large and sophisticated spacecraft to missions comprised of large numbers of simple microspacecraft or picospacecraft. Only by flying 100 s of spacecraft and thereby obtaining simultaneous high spatial resolution vector field and plasma measurements over a significant fraction of the entire magnetosphere will it be possible to understand the energy flow and coupling between different regions in the Earth’s magnetotail. Such magnetospheric constellation-type missions will revolutionize our view of the magnetosphere by resolving spatial and temporal ambiguities, determining the scale size of processes and regions, and reveal connections between the different regions of the magnetotail.

However, the current generation of plasma spectrometers, e.g., those recently flown on missions such as Cluster II, THEMIS, and Magnetospheric MultiScale, are too massive (roughly 6 kg), consume too much electrical power (several watts), and require too much assembly and testing time to be flown on future multispacecraft microsatellite missions (total spacecraft mass less than 10 kg and total power less than 5 W [Frost, 2014]).
Building large quantities of these instruments for missions that would include many identical payloads would also be prohibitively expensive. Advanced wafer-scale fabrication techniques naturally lend themselves to relatively high manufacturing volumes (even for large sensors) and therefore change the paradigm for dealing with flaws or defects in individual instruments.

There are essentially three elements in any plasma spectrometer: a collimating structure that defines the viewing geometry of the instrument and, ideally, provides partial or complete shielding of the instrument from sunlight, an energy per charge or energy per mass resolving analyzer (this element could also be a simple time-of-flight detector that only provides particle velocity), and a particle detector. Here we focus on improving the collimator and analyzer elements through the use of advanced wafer-scale fabrication techniques. Solid-state detectors already exist and are briefly discussed later in this manuscript.

1.1. Collimators

For collimation, a classic "conventional" plasma spectrometer typically employs some structure to narrow the field of view for the desired particles. If the target species is neutral, the collimator typically incorporates alternating bias potentials of a few kilovolts to sweep out all the incoming charged particles. In some cases, such as in a top-hat design [Young et al., 1988], the collimator is part of the electrostatic optics of the instrument acceptance angle over a large range of incident trajectories. For compact plasma spectrometers developed over the last decade, micromachined structures have been introduced as collimators [Wesolek et al., 2005].

Some examples of existing collimators are shown in Figure 1. In Figure 1a, the classic parallel plate collimator built for each of the three heads of the Medium Energy Neutral Atom (MENA) instrument on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) mission [Pollock et al., 2000] is shown. The MENA collimator was a separate structure with alternating high-voltage plates designed to sweep out charged particles.
and only permit the passage of neutral atoms. The narrow gap between the biased plates limited the transverse view to ±4° in one plane with slightly more than 120° of view in the imaging direction. Figure 1b shows a schematic of the LEP-ESA/ISA (Low Energy Particle-Electron Spectrum Analyzer/Ion Spectrum Analyzer) toroidal top-hat electrostatic analyzer. The arcs of the inner curved plates terminate at a flat surface. The lower surface and an upper flat plate form part of a circular collimator and deflector. Between the flat surfaces, an electric field deflects downward any particles passing through that region. Because the electric field in the collimator region deflects particles only in a plane, central force deflection does not begin until particles enter the toroid [Young et al., 1988]. A key point is that decreasing the collimator spacing improves the background light rejection at the cost of reduced particle throughput.

Figure 1c shows a schematic of the compact collimator developed for the Flat Plasma Spectrometer (FlaPS) plasma instrument [Wesolek et al., 2005]. The collimator consists of two mask layers: one mask for the frontside etch pattern and one for the backside etch pattern. The etching was performed at the wafer level with the deep reactive ion etching (DRIE) process for 400 μm thick wafers. On the frontside of the wafer, 140 μm × 140 μm square holes (apertures) were etched to an approximate depth of 70 μm. On the other side of the wafer, using the other mask, 300 μm × 300 μm holes were etched to a depth of approximately 330 μm; intersecting the holes coming from the other side. After etching from above and below, five collimator plates were stacked together to form a 2 mm thick collimating structure. The excellent ±4° × 4° angular acceptance in such a compact object came at the cost of a poor overall transmission of 6% because of the large spacing of the backside apertures. The poor transmission resulted from the need to space the collimating apertures (140 μm) by at least 300 μm to accommodate the back side apertures.

1.2. Energy Analyzers

To reduce the effects of sunlight on the detectors while measuring particle energies, a plasma spectrometer typically introduces a significant path deflection for charged particles but not for light. Photons entering the instrument meet some physical obstruction while the desired charged particles are electrostatically guided around the obstruction. If the target particles are neutral, electrostatic guiding is not possible, and other methods for background light reduction are used. For example, the IMAGE MENA instrument [Pollock et al., 2000] and the Two Wide-angle Imaging Neutral-atom Spectrometers energetic neutral atom instruments [McComas et al., 2009] employed submicron period gold gratings to reduce background light levels by over 6 orders of magnitude [Balkey et al., 1998] while still permitting the passage of neutral atoms.

Having been flown so often, the toroidal top-hat electrostatic plasma energy analyzer shown in Figure 1b is nearly a standard in plasma spectrometers. For example, the Fast Plasma Investigation (FPI) [C. J. Pollock et al., Fast Plasma Investigation for Magnetospheric Multiscale, submitted to Space Science Reviews, 2015] on the Magnetospheric Multiscale (MMS) spacecraft is composed of dual top-hat analyzers with an energy range of 10 eV to 30 keV for ions and electrons, and when combined with three other identical instruments on every spacecraft platform, it is capable of acquiring fully 3-D ion and electron energy distributions at a measurement cadence of 30 ms for electrons and 150 ms for ions. Even more advanced electrostatic geometries have been developed to provide mass resolution or other features. The ion mass spectrometer (IMS) component of the Cassini Plasma Spectrometer instrument package is an excellent example of a customized electrostatic field structure analyzer that provides both mass and energy resolution in a plasma analyzer [McComas and Nordholt, 1990].

The superb measurement characteristics of the FPI and IMS instruments come at the price of masses approaching 10 kg and power consumption approaching 10 W. Shown in Figure 1c is a radically different approach for electrostatic energy analysis. The Flat Plasma Spectrometer (FlaPS) employed the etched collimator structure noted previously and straight micromachined, electrically biased, channels to deflect ions of energies up to 50 keV past a blocking mask [Wesolek et al., 2005]. FlaPS had a volume of 400 cm³ at a mass of 0.5 kg and required 750 mW of power. The channels for FlaPS were fabricated with microelectrical discharge machining. The FlaPS instrument’s energy selection scales as (1/4f)(L/ΔX)², where L = 2 mm is the plate length, ΔX = 0.5 mm is the spacing between the electrodes, and f = 0.4 is the fraction of the spacing between the electrodes used for energy analysis. Therefore, a differential voltage of 2000 V is required to deflect a 20 keV singly charged ion around the light blocking baffle at the exit plane of the parallel plate assembly [Wesolek et al., 2005]. Since the target ionospheric plasmas for the FalconSAT 3 mission, which included the FlaPS instrument, have temperatures of less than a few eV, an instrument voltage supply of only 10 V
was sufficient. For magnetospheric and heliospheric ions at energies of tens of keV, the electrostatic optics of a FlaPS-type energy analyzer require large bias voltages that are inconsistent with a low-power, low-complexity, compact plasma instrument.

However, the energy selection scaling of a curved plate analyzer is \( E = (q\Delta V)/(2 \ln(1 + \Delta r/R_i)) \), where \( R_i \) is the inner plate radius and \( \Delta r \) is the plate spacing. For closely spaced plates, the transiting energy reduces to \( E = q\Delta V/2\Delta r \) to first order, i.e., the energy scales with the radius of the analyzer divided by twice the plate spacing. The focusing properties of a cylindrical curved plate analyzer are optimal for a bending angle of 127° [Hughes and Rojansky, 1929]. For curved plates spanning 127°, charged particles injected at the center of the analyzer plates but with a wide range of incident angles successfully pass through the analyzer and are focused upon exiting the analyzer. For a spherical or “top-hat” analyzer, the optics are slightly different. Typically a smaller bending angle is used and two-dimensional electrostatic focusing is sacrificed so that a fully two-dimensional aperture is achieved, which significantly improves the geometric factor of the instrument. Conventional manufacturing constraints and the need to maximize the size of the input aperture set the scale of the spacing between the curved plates. In the hemispherical analyzer of Young et al. [1988], the plate spacing is 0.5 cm and a differential voltage of 2350 V is required to convey ions with 20 keV/charge around the plates and into the detector. When top-hat analyzers are miniaturized, either the required bias voltage must increase if large plate spacing, and therefore, the geometric factor is to be preserved, or the plate spacing must shrink at the expense of the geometric factor.

Research teams building plasma instruments for recent and upcoming CubeSat missions have devised creative solutions to challenges of minimal weight and power. The SupraThermal Electrons, Ions and Neutrals (STEIN) instrument on the recently launched CubeSat for Ions, Neutrals, Electrons, MAgnetic fields (CINEMA) CubeSat uses a large angular acceptance with minimal light baffling and a 4 pixel, low-energy detection threshold solid-state detector for detection of ions, electrons, and neutrons [Glaser et al., 2009]. A high voltage across two parallel plates deflects incoming, low-energy, positive (negative) species upward (downward), while high-energy charged particles and all neutrals hit the inner 2 pixels of the array of four vertical pixels. Energy information is provided entirely by the solid-state detector. The entire STEIN instrument fills a volume of roughly 5 cm × 5 cm × 5 cm. The selected, but not yet launched, CuSSP CubeSat mission proposes to use a miniaturized version of the Suprathermal Ion Sensor (SIS) to measure suprathermal ions (tens of keV to tens of MeV/nucleon). The SIS instrument employs high voltages across a pair of closely spaced curved plates to deflect ions of a wide energy range onto an annular microchannel plate detector. The spatial distribution of detected ions corresponds to their incident energies [Allegrini et al., 2014]. The ELFIN (Electron Losses In Fields INvestigation) CubeSat mission currently under development will also use a miniaturized, solid-state detector-based, energetic particle telescope to investigate relativistic radiation belt electrons and ions (energies > 50 keV) (elfin-lomo.lgpp.ucla.edu, accessed 6 January 2016).

Here we report test results for a medium-energy range (5–20 keV) plasma spectrometer concept that employs a high transmission efficiency, lithographically fabricated collimator, and a layer of tightly spaced curved-plate analyzers. The collimator achieves a ±1.5° × ±1.5° angular acceptance in a structure only 640 μm thick with ~20% transmission efficiency (and >45% transmission appears readily achievable). Each energy analyzer layer, or “chip,” consisting of eight bands of curved plates with each band containing 10 discrete curved channels between the curved plates, achieves an aperture efficiency of 22%. A single pair of curved plates requires a potential difference of only 10 V to select charged particle energies/charge of 20 keV. Although not described in detail here, the full design concept includes a solid state detector with a detection threshold of 5 keV for ions and 3 keV for electrons for a detector bias of only 100 V. Therefore, the entire plasma spectrometer concept requires a single DC power supply of no more than 200 V to obtain an eight band energy/per charge spectrum beginning at the energy threshold of the detector and ending at approximately 20 keV. Because the spectrometer elements are lithographically fabricated in silicon, large numbers of identical elements can be created on a single, large-diameter silicon wafer.

## 2. Collimator Design and Testing Results

The design target for the collimating structure was a transmission of 44% and a ±2° × ±2° angular acceptance. We employed DRIE processing to fabricate collimating apertures of 28 μm × 28 μm in a 100 mm diameter, 320 μm thick, <100> crystalline axis orientation, heavily P/Boron-doped (resistivity < 0.005 Ω cm) silicon wafer (see Figure 2a). For the 40 μm center-to-center spacing of the apertures, the theoretical transmission
efficiency of the wafer is 49%. To obtain the desired angular acceptance, the design assumes two collimator chips will be stacked atop each other and the apertures aligned. The chips are then bonded together. The apertures we fabricated with the initial DRIE process narrowed down from 28 \( \mu \text{m} \) on the frontside to approximately 17 \( \mu \text{m} \) on the backside of the wafer (see Figure 2b). This aperture taper reduced the effective measured transparency to about 20%. Improvements to the etching recipe can mitigate or eliminate the narrowing of the holes in deep etches. However, the results reported here are based on tests employing the first set of fabricated collimators which had the 28 \( \mu \text{m} \) to 17 \( \mu \text{m} \) taper.

Shown in Figure 3 is a scanning electron microscope (SEM) image of the interface between two collimator wafers that have been bonded together. The wafers were stacked with the sides with the larger, 28 \( \mu \text{m} \times 28 \mu \text{m} \), holes facing each other to minimize particle scattering off the walls inside the collimator and to provide the maximum angular acceptance constraint. For an overall thickness of 640 \( \mu \text{m} \), the expected angular acceptance of the collimator stack is \( \pm 1.5^\circ \times \pm 1.5^\circ \) and the expected transmission efficiency is 18%. The collimator’s aperture pattern on each layer was divided into eight identical collimator regions, which are designed to line up with the eight energy analyzer regions of the full device.

Testing of the collimator stack was performed with a variable energy electron beam in the Space Plasma Instrumentation Facility at Goddard Space Flight Center. The collimator was placed in front of an imaging microchannel plate beam profile monitor, and the absolute transmission through the collimator stack was measured as a function of the angle of the collimator stack to the beam direction (in both angular directions). Shown in Figure 4 is an image of the transmitted flux of 1 keV electrons through two of the collimator regions for the collimator stack. The peaking in the vertical direction in the transmitted intensity at the center of each of the two regions with the apertures in Figure 4 is a result of the divergence of the incident electron beam. In other words, the angular acceptance of the collimator stack is comparable to the angular spread of the electron beam, and therefore, only the center of the electron beam is maximally transmitted. As the collimator stack is rotated, the transmission increases at the sides of the regions with the apertures. The transmitted electron flux as a function
of horizontal angle is shown in Figure 5 for a vertical slice through the collimator region closest to the center of the electron beam. The peak measured transmission is nearly 20%, very close to the predicted value of 18%. A Gaussian fit to the measured angular response yields a full width at half maximum of 1.1°, and the transmission cuts off at ±1.5°, exactly as predicted. Even using the first generation of collimator wafers, the transmission efficiency is already three times larger than those used for the FlaPS instrument; with improved angular resolution. Given these results, an overall collimator transmission of over 40% with a ±2° × ±2° angular acceptance appears to be readily achievable.

3. Energy Analyzer Design and Testing Results

Shown in Figure 6 is a conceptual design for a single layer containing eight curved plate energy analyzer bands etched into highly conductive silicon. Note that the energy analyzer “wafer” is a wafer-to-wafer bonded pair; the upper wafer is highly doped and subject to the DRIE process; the lower wafer is an insulating wafer, serves as an etch stop, and also maintains electrical isolation from one free standing plate to the next. In this design, each band consists of nine mechanically independent and isolated curved plates yielding 10 channels per band. The angle of curvature is such that photons entering the gap between the plates will have to undergo a single reflection to pass through the curved plate system. As described in the recent review by Gilbert et al. [2014], a single bounce is typically insufficient for significant background ultraviolet light rejection and the angle of curvature will be adjusted in future versions of the curved plate pairs based on the need for background light rejection (some missions may not require significant background light rejection, i.e., an antisunward pointing instrument on a nonrotating spacecraft). The light scattering properties of these micro-scale structures is unknown and future plans include measurements of the ultraviolet light transmission through the curved plates. The design target for the curved plates in each band was 300 μm high with 10 μm thickness and a plate-to-plate gap of 80 μm. For these parameters, the plate radius to plate spacing ratio (R/Δr) is 3750, and a potential difference of only 10.7 V across two plates would therefore be sufficient to transport ions with energy/charge of 20 keV from the entrance aperture to the exit aperture.

The critical feature in this design is that the large number of curved plate pairs contained in eight distinct bands maximizes the effective working aperture area of the analyzer while also naturally creating an energy spectrometer. For a 100 μm thick base (lower wafer of the two wafer system) under the plates, the design...
shown in Figure 6 would have an active aperture to total surface area ratio of 48%. In other words, 48% of the target species falling on the entrance side of the layer will be filtered based on their energy per charge. The eight distinct bands allow for eight different energy ranges to be simultaneously sampled for distinct electric potential differences applied to the larger electrode “pads” that are in between the eight sets of curved plates. Therefore, this design provides for measurements of energy spectra using only DC voltage supplies and with a 100% duty cycle in terms of energy analysis; i.e., the design energy spectrum of the instrument is measured at all times. The potentials on the individual plates in each band are determined by a thin film resistive layer connecting tops of the larger pads to the plates in between (additional details concerning this geometry are provided below). For example, beginning at one end, seven different constant potentials applied to the larger pads in a pattern of 100 V, 0 V, 50 V, 75 V, 25 V, 62.5 V, 87.5 V, 0 V, and 25 V create energy passbands of 20 keV/e, 10 keV/e, 5 keV/e, 2.5 keV/e, 7.5 keV/e, 12.5 keV/e, 17 keV/e, and 15 keV/e, respectively. This particular applied voltage pattern is chosen to minimize the number of distinct voltages that are required to cover the full energy range (each large pad plays a role in biasing two bands of plates). Note that the electrical contacts on the underside of the base are fabricated through two-sided lithography.

Another key feature of this analyzer design is that each energy analyzer structure is intended to be a single layer in a large stack of identical layers. Shown in Figure 7 is a schematic of a stack of 25 energy analyzer layers. The entire structure is approximately 1 cm deep, 1.5 cm high, and 1.75 cm in width, just slightly larger than a standard sugar cube and slightly larger than the design objective of 1 cm × 1 cm × 1 cm. The eight energy bands, duplicated identically in each of the 25 layers, are visible on the “entrance” side of the stack, and electrical interconnects, not shown, will run along the face of the stack to connect the larger electrode.
pads into identically biased columns of electrodes. The thin film resistive layer that connects individual plates to the larger pad electrodes is placed on the underside of the layer above using a two-sided lithography process. The top layer of the energy analyzer chip stack is a separately fabricated electrical connection chip which utilizes a “thru via” approach and double-sided lithography so that a single flex cable mounted to the top of the stack provides all the bias voltages for the entire stack. The multichip collimator assembly is mounted on the entrance aperture side of the stack to restrict particle fluxes to the desired look direction and to improve the energy selectivity of the analyzer stack by creating a collimated beam of incident particles. The collimator assembly includes a transparent noncollimating transposer layer which serves as the third chip of the collimator chip stack. This transposer chip has the nine vertical strips of conductors that deliver voltage from the upper electrical connection chip to the other levels.

The energy analyzer plates were fabricated using DRIE in 350 μm thick <100> heavily P/Boron-doped (resistivity < 0.005 Ω·cm) silicon on a 200 μm thick layer of <100> P/Boron-doped (resistivity > 1000 Ω·cm) silicon with 2 μm thick buried oxide layer. Three SEM images of a completed energy analyzer layer are shown in Figure 8. In Figure 8a, an entire set of plates is visible. The gaps between the plates are clear of debris, and the plates are etched down to the insulating baseplate layer. In the expanded views of Figures 8b and 8c, it is clear that the plates are nearly as thick as the gap in between the individual plates. Undercutting of the plates during DRIE processing, highlighted in Figure 8c, prevented fabrication of 10 μm thick plates as originally designed. To ensure plate stability for prototype testing, we fabricated analyzer plates with 60 μm thick plates. The additional plate thickness
is responsible for the 1.75 cm width of the analyzer chip as shown in the 3-D stack of Figure 7 and reduces the theoretically achievable active area of the analyzer stack to 27%. Based on analysis of a series of plate thickness scaling fabrication runs and the resulting mechanical stability of the plates, the current undercut size will likely restrict the minimum plate thickness to about 30 μm, placing an upper limit on the active surface area of a complete analyzer stack of approximately 35%. With an aperture fraction of 35%, the active collection area of the instrument concept shown in Figure 7 is 0.48 cm². For comparison, the total active aperture of the conventional top-hat analyzer described by Young et al. [1988] is 2.11 cm², only a factor of 5 difference. In other words, a set of five of these ultracompact plasma spectrometers would have the same active aperture area of a much larger top-hat analyzer. A close up view of four energy analyzer layers in a stack is shown in Figure 9. This stack is not interconnected but rather serves as a demonstration of the layer alignment process. Layers ready for 3-D stacking will have the double-sided lithography electrical contact pattern.

For these initial tests, a single energy analyzer layer was mounted upside down on a glass substrate upon which individual electrical contacts for each plate and large electrode were deposited. The electrical connection layer was fabricated specifically for testing and allowed for direct measurement and application of the voltages on each of the nine plates in two bands. Note that because the potential difference applied between two plates is at most a few volts, it should be impossible to create an electrical discharge in between the plates even though the electric field between two plates is large enough to deflect charged particles of energies up to tens of keV/e (the voltage difference between any two plates is comparable to or smaller than the ionization potential of atmospheric gasses, and therefore, an ionization cascade is difficult to initiate). A 5 keV electron beam was directed to the entrances of the eight energy analyzer bands, and the flux of any electrons passing through the bands in the single analyzer layer was measured with an imaging microchannel plate (MCP) beam profile monitor placed behind the energy analyzer layer. Because of the geometry of the mounting structure, a gap through which unblocked electrons could pass remained just above the energy analyzer layer. Therefore, for all measurements, a wide, thin region of intense flux of electrons was recorded by the imaging detector just above the energy analyzer structure. Data were acquired over 10–30 min with and without bias applied to the energy analyzer plates, and

Figure 8. Scanning electron microscope images of the energy analyzer structure. (a) A side view from the entrance side of two bands of energy analyzer. (b) The structure of a single section of plates showing the 80 μm plate-to-plate spacing and plates that are 60 μm in width. (c) An expanded view of the base of a single 60 μm wide plate showing the undercutting that occurs at the interface of the plate material and the insulating substrate. This undercutting results from the reduced molecular flow in the DRIE process at 90° corner boundaries.
difference images were created to eliminate the background signal created by the unblocked electrons. The difference image shown in Figure 10 was obtained for a bias of 26.6 V applied to the third analyzer band in a set of eight analyzer bands. The voltage difference between each pair of plates was set with a voltage divider consisting of ten 5 kΩ resistors in series, with each resistor junction being mapped to an individual plate through the custom electrical breakout layer bonded to the top of the plates. The individual traces on the custom breakout layer were covered with a ground plane to prevent voltages applied to the plates from distorting particle trajectories. The imaging MCP system has a spatial resolution of roughly 100 μm (a result of the 8 bit data acquisition electronics used). Therefore, we expect an individual band of 10 channels to appear as a structure approximately 2–3 pixels high and 12–14 pixels wide. The flux shown in Figure 10 corresponds exactly to the location of the band that was biased and has the expected spatial scale. The peak transmission through the band (normalized to the beam flux and background levels) was 25%, very close to the 27% expected given the dimensions of the plates, the substrate thickness, and the spacing between the plates. These measurements demonstrate that the 10 analyzer plate pairs biased properly, that all 10 analyzers functioned as a single energy analyzer unit, and that the transmission efficiency was consistent with the fraction of open area of the band. In particular, the heavily doped silicon wafer material appears to be conductive enough to function as an electrode in this application. Note that a single gap of the same total voltage difference and as wide as the full band would transmit charged particles with the same energy/charge and with a larger transmission efficiency. However, by breaking the structure up into 10 identical channels, photons are prevented from direct access to the detector and the very small voltage difference across any two plates (only 2.66 V per gap was required to analyze 5 keV electrons in this case) ensures that it is impossible to create a discharge or arc across the gaps during testing in air or at moderate vacuum pressures. Based on SIMION™ simulations, the expected energy resolution of a single analyzer band is approximately 20%. Shown in Figure 11 is the flux through the single analyzer band as a function of electron beam energy (normalized to the incident beam flux after background subtraction). Unfortunately, only a partial beam energy scan was completed due to limited time and difficulties with the electron beam facility. Assuming that the energy response obeys a Gaussian function, a fit to the measurements shown in Figure 11 yields a standard deviation of 1200 ± 200 eV, i.e., an energy resolution (standard deviation/central value) of roughly 24%. The data are too sparse to provide a more precise value.

4. Detectors and Overall Geometric Factor

While in this work we do not provide measurements demonstrating the properties of the detector intended for use in this instrument concept, the detection scheme is a critical element of creating a low-voltage plasma spectrometer. The detector is the third key solid state element of the 3-D microscale plasma spectrometer. In conventional plasma spectrometers, detection of ions and electrons at energies less than 30 keV is typically accomplished with either discrete channel electron multipliers [Bame et al., 1992] or microchannel plates [Young et al., 1988]. Both approaches require high-voltage power supplies (~2–3 kV) to create the pulse amplifying electron cascade. Even simple plasma instruments, such as the Faraday cup style detectors aboard the Voyager spacecraft, still require fairly high voltages to repel the energetic ions of the solar wind [Bridge et al., 1977]. Silicon solid state detectors (SSSDs) which require bias voltages of only a few tens of volts...
to 100 V have historically had energy thresholds of tens of keV. The energy threshold is determined by thickness of the detector contacts and the intrinsic detector capacitance. According to Tindall et al. [2008], “The electric field does not penetrate the contact fully and hence electron hole pairs created in this field free region have a significant probability of recombining before they can be collected. Incident particles that are not energetic enough to enter the active region of the device will not be detected. For silicon detectors with contacts that have been fabricated using standard ion implantation techniques the junction depth has been reported to be about 3000 Å, a window thickness corresponding to about a 30 keV threshold for protons (20 keV for electrons).” However, recent advances in lowering the energy threshold for SSSDs now make it possible to construct an array of thin-contact, passively cooled, solid-state detector pixels with a lower energy threshold of only 2 keV for electrons [Tindall et al., 2008]. Suggested for use in plasma instruments by Ritzau et al. [1998] who demonstrated their suitability in laboratory experiments, thin-contact SSSD detectors are now in use in space in the In-situ Measurements of Particles And CME Transients SupraThermal Electron instrument [Lin et al., 2008], in the Solid State Telescopes on the THEMIS mission [Angelopoulos, 2008], and in the STEIN instrument on the CINEMA spacecraft as noted previously. In addition to operating with modest bias voltages (less than 100 V), SSSDs also have lower background count levels than electron multipliers, and like an electron multiplier they measure all charged particles above their energy threshold simultaneously, i.e., a 100% duty cycle; while also providing independent measurement of the incident particle energy.

For the purposes of calculation of overall instrument geometric factor and energy range, we assume here that this instrument will employ low-power consumption SSSDs [Tindall et al., 2008] with an energy threshold 1.1 keV for electrons and 2.3 keV for ions. When electronic noise is included, this corresponds to a low-energy limit of 5 keV for ions. We assume eight discrete detector pixels are aligned with each vertical column of energy analyzer bands (see Figure 7). As an aside, we note that the particle energy measurement provided by the SSSD is available for noise rejection of each count. If the SSSD measured energy does not fall within with the pass band of the energy analyzer in front of that SSSD pixel, the count can be
The key figure of merit for a plasma instrument is its geometric factor, i.e., the effective collection area. Too small of a geometric factor and the instrument is unable to generate a statistically significant count rate for the target local plasma conditions. For the instrument design shown in Figure 7, the geometric factor is

$$G = \alpha \chi A \gamma \text{cm}^2 \text{sreV/eV},$$  \hspace{1cm} (1)

where $\Delta \alpha$ is the two-dimensional angular acceptance of the combined collimator and analyzer structure, $\chi$ is the transparency of the collimator, $A$ is the total area of the electrostatic analyzer apertures, and $\gamma$ is the normalized energy resolution of the instrument $(\Delta E/E)$. For a given uniform flux of ions incident on the collimator, the product of the flux and the geometric factor gives the number of ions that pass through the instrument and fall onto the solid-state detector. Collinson et al. [2012] provide a useful expression for estimating the geometric factor of an electrostatic analyzer from the results of a ray-tracing simulation,

$$G = \frac{CA_{i}E_{b}\cos^{2}(\theta_{b})\Delta E_{b}\Delta \theta_{y} \Delta \phi_{y}}{NE_{o}^{2}} \text{cm}^2 \text{sreV/eV},$$  \hspace{1cm} (2)

where $C$ is the number of particles that exit the analyzer from the total of $N$ injected; $A_{i}$ is the area of the source region of test particles with average energy $E_{b}$, average polar angle $\theta_{b}$ over polar range $\Delta \theta_{b}$ and azimuthal angle range $\Delta \phi_{y}$ and $E_{o}$ is the central passing energy of the analyzer. A full 3-D SIMION model of a representative section of the proposed instrument was illuminated with a uniform flux of ions (random injection angles and across a single channel), and the resultant transmitted fraction was measured. The single channel geometric factor obtained from equation (2) multiplied by 2000 to account for the number of channels across the face of a full analyzer stack is $G = 3.7 \times 10^{-5} \text{cm}^2 \text{sreV/eV}$. While small, the geometric factor calculated here is easily increased by increasing the angular field of view at the expense of decreasing the energy resolution. For example, increasing the field of view to $\pm 20^\circ \times \pm 20^\circ$ (more typical of the plasma instruments being proposed for CubeSat missions), and assuming such an increased angular spread in the incident particles still gets through the curved plate analyzer section, increases the angular terms in the geometric factor by a factor of 100. The energy resolution term in the geometric factor would also increase; the exact amount would have to be determined through numerical simulation or laboratory measurement.

The measured count rate from the proposed instrument is a function of the local plasma conditions. For the instrument design shown in Figure 7, the geometric factor is

$$G = \Delta \alpha \chi A \gamma \text{cm}^2 \text{sreV/eV},$$  \hspace{1cm} (1)

where $\Delta \alpha$ is the two-dimensional angular acceptance of the combined collimator and analyzer structure, $\chi$ is the transparency of the collimator, $A$ is the total area of the electrostatic analyzer apertures, and $\gamma$ is the normalized energy resolution of the instrument $(\Delta E/E)$. For a given uniform flux of ions incident on the collimator, the product of the flux and the geometric factor gives the number of ions that pass through the instrument and fall onto the solid-state detector. Collinson et al. [2012] provide a useful expression for estimating the geometric factor of an electrostatic analyzer from the results of a ray-tracing simulation,

$$G = \frac{CA_{i}E_{b}\cos^{2}(\theta_{b})\Delta E_{b}\Delta \theta_{y} \Delta \phi_{y}}{NE_{o}^{2}} \text{cm}^2 \text{sreV/eV},$$  \hspace{1cm} (2)

where $C$ is the number of particles that exit the analyzer from the total of $N$ injected; $A_{i}$ is the area of the source region of test particles with average energy $E_{b}$, average polar angle $\theta_{b}$ over polar range $\Delta \theta_{b}$ and azimuthal angle range $\Delta \phi_{y}$ and $E_{o}$ is the central passing energy of the analyzer. A full 3-D SIMION model of a representative section of the proposed instrument was illuminated with a uniform flux of ions (random injection angles and across a single channel), and the resultant transmitted fraction was measured. The single channel geometric factor obtained from equation (2) multiplied by 2000 to account for the number of channels across the face of a full analyzer stack is $G = 3.7 \times 10^{-5} \text{cm}^2 \text{sreV/eV}$. While small, the geometric factor calculated here is easily increased by increasing the angular field of view at the expense of decreasing the energy resolution. For example, increasing the field of view to $\pm 20^\circ \times \pm 20^\circ$ (more typical of the plasma instruments being proposed for CubeSat missions), and assuming such an increased angular spread in the incident particles still gets through the curved plate analyzer section, increases the angular terms in the geometric factor by a factor of 100. The energy resolution term in the geometric factor would also increase; the exact amount would have to be determined through numerical simulation or laboratory measurement.

The measured count rate from the proposed instrument is a function of the local plasma flux, the geometric factor, the duty cycle of the device, and the overall detection efficiency. In a conventional spectrometer, the detection efficiency depends on the conversion efficiency of the microchannel plate or channel electron multiplier as well as the efficiency of the detector electronics. In fact, the conversion efficiency of microchannel plates drops a factor of 2 over the energy range 1 to 10 keV for electrons [Collinson et al., 2012]. SSSDs, however, are nearly 100% efficient in detecting ions that make it through the contact layer. Therefore, the overall geometric factor (including detection efficiencies and collimator transparency) of the proposed ultracompact spectrometer is $G = 1.6 \times 10^{-5} \text{cm}^2 \text{sreV/eV}$. For comparison to conventional plasma instruments,
the geometric factor should be reduced by a factor of 8 to account for the fact that the total incident flux is divided into eight distinct energy bands. Whereas in a conventional plasma spectrometer the electrostatic analyzer voltage is swept through a series of fixed voltages, here the entire energy band is continuously sampled. As noted previously, typical duty factors are on the order of 8%, so the increased duty cycle of this spectrometer more than compensates for dividing up the total incident flux into the distinct energy bands. For comparison, the FPI instrument for MMS has a geometric factor of $G = 2 \times 10^{-4}$ cm$^2$ sr (eV/eV) per imaging pixel at 20 keV [Collinson et al., 2012]. When integrated over the entire field of view, the total FPI geometric factor increases by roughly another order of magnitude.

5. Conclusions

Laboratory electron beam tests of a lithographically MEMs-fabricated collimator and a lithographically MEMs-fabricated energy analyzer are consistent with calculations based on the mechanical design of the components. The angular resolution and transmission of the collimator exceeds that of previously micromachined collimating structures. The overall transmission, energy per charge scaling, and energy resolution of the energy analyzer are in excellent agreement with the design targets. Therefore, with appropriate electrical interconnects, it appears possible to construct a stack of energy analyzer layers that will have a large active aperture surface area to instrument volume ratio. Aligning, stacking, and binding together the energy analyzer layers require the same apparatus currently used in multilayer silicon chip manufacture, so while not trivial, the stacking process is well understood. With the addition of a SSSD, the entire instrument could be powered with a single DC voltage supply capable of sourcing no more than 100 V and a few milliamps of current. Once mounted into a mechanical fixture, the entire instrument could fit into a volume of 1.5 cm × 1.5 cm × 1.75 cm. The power supply, other electronics, and communication bus interface could be placed on a single custom circuit board onto which the instrument is mounted.

Such an instrument would have a geometric factor roughly a factor of 10 smaller than the per line-of-sight (single pixel) geometric factor of a conventional plasma spectrometer and would have a fixed line of sight. To increase the spatial coverage or the overall geometric factor of this type of instrument, a collection of these ultracompact plasma spectrometers could be used in parallel. Note that the geometric factor of this type of instrument scales linearly with any dimension of the instrument, whereas conventional instruments grow in volume as the surface area of the aperture increases. In other words, 100, e.g., a 10 by 10 array, of these ultracompact plasma spectrometers placed on the side of a CubeSat would have a geometric factor that exceeds a conventional plasma spectrometer but would still only be a layer approximately 15 cm × 17.5 cm in area and 1.5 cm thick including the detector. All 100 ultracompact spectrometers could share a single DC power supply and readout electronics.

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References


