Particle Radiation Near the Orbit of the Vacuum Wake Shield

Edgar A. Bering III* and Alex Ignatiev†
University of Houston, Houston, Texas

The particle populations that are expected to inflict the most damage on thin film materials grown on the vacuum Wake Shield Facility (WSF) are ions and energetic neutral atoms with energies in the range of 100 eV to 20 keV. The production of films that have an order of magnitude fewer defects than are now available requires that the 1-keV particle flux be kept lower than 10^3 particles/(cm^2 s sr keV) (assuming a reasonable spectral shape). WSF will be flown on orbits with an inclination of 28 deg at altitudes of 300–700 km. Because of the background counting rate produced by the ~100 MeV trapped protons in the inner belt, obtaining accurate measurements of the particles of interest is very difficult. The quiet-time background fluxes of the relevant particles are not presently known. At times of magnetic activity, fluxes of 0.1–17 keV O^+ ions as great as 10^7 ions/(cm^2 s sr keV) have been observed flowing out of the ionosphere at these latitudes. It appears that instrumentation for detailed assessment is essential for the proof-of-concept flight(s) and that real-time monitoring of low-energy ion and energetic neutral radiation will be required for the production flights.

Nomenclature

dN/dE	= omnidirectional particle flux in particles, (cm^2 sr s keV)$^{-1}$
E	= particle energy in keV
L	= McIlwain's L parameter. For a dipole magnetic field, L is the equatorial crossing distance of a magnetic field line measured in Earth radii
N_D	= defect density in defects, cm^{-3}
R_E	= radius of the Earth
spread – F	= a type of ionospheric turbulence, identified by its appearance in ionograms
v_s	= epitaxial growth velocity of a thin film surface

Introduction

THE Wake Shield Facility (WSF) will be a prototype orbital manufacturing facility dedicated to the production of epitaxially grown thin-film semiconductor and superconductor devices that require the difficult combination of ultrahigh vacuum and high pumping rates in their manufacture. As currently envisioned, WSF will be a ~4-m-diam flat circular dish flown in low L-value low Earth orbit (LLLEO).[1,2] During experiments on orbit, the shield will be oriented with one surface facing forward along the direction of flight. The volume of enhanced vacuum in the near wake of the shield is the region that will be used for film growth. Nominally, a pressure of 10^{-11} Torr is expected during tethered operations. A target pressure of 10^{-14} Torr has been set as a design goal for free-flyer operation during solar minimum.

The WSF will carry the equipment required to grow thin films using molecular beam and chemical beam epitaxy on the rear surface. This equipment will include a minimum of eight sources (thermal and gaseous) for the deposition of thin film materials, a substrate holder and carousel for substrate manipulation, and source shutters and a computer to control the sources. The crystalline quality of the grown films will be monitored by reflection high-energy electron diffraction. Instrumentation to monitor the local vacuum wake environment will include a mass spectrometer. The WSF will be deployed initially on the remote manipulator arm in the shuttle cargo bay (STS RMS) with the expectation of future deployment as a free flyer in a 700-km circular orbit. The neutral gas, plasma, and radiation environments in the vacuum wake of the WSF will all affect the quality and value of the devices produced. In this paper, an upper limit on the tolerable penetrating particle flux will be calculated. Second, an assessment will be made of the penetrating particle radiation in the energy range that is most likely to damage semiconductor devices that are being manufactured. Recommendations are made regarding the shielding and monitoring that may be required.

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*Professor, Physics Department and Space Vacuum Epitaxy Center.
†Director, Space Vacuum Epitaxy Center and Professor, Physics Department.

Flux Limit Calculation

The particles that do the most damage to a growing semiconductor device are those that stop and deposit their energy near the surface of the device, in what will ultimately be the active volume of the device. The particles that will stop in the volume of interest, and that deposit enough energy to cause significant damage, are ions with energies between 0.1 and 20 keV.[3,4] Below 100 eV, incident ions are more likely to scatter from a surface than to penetrate the lattice. Furthermore, the velocity of 100 eV O^+ (singly charged oxygen atom) ions is comparable to the orbital velocity of the WSF, which means that the shield will begin to be effective in reducing incident flux at about this energy. Above 20 keV, the stopping range of the ions becomes so much greater than the thickness of the region of interest in the film that this region can be considered effectively transparent. Laboratory data on the effect of O^+ bombardment of semiconductors do not exist. Extrapolation from experiments done using N_2^+ (which dissociates that the surface into two N^+ ions) to bombard metal targets suggest that an O^+ ion in this energy range will stop within 5 nm of the surface and will create $\sim 10^2 E^{0.3}$ defects (mainly interstitials and vacancies) while stopping.[5] Annealing during the manufacturing process will remove 90% of these defects.[6] The best currently available epitaxially grown thin film materials have a defect density of 10^{14} cm^{-3}. A preliminary design target of at least a one order of magnitude improvement in this figure has been established. It is estimated that if the design vacuum levels are achieved, a chemical defect density of 10^{12} cm^{-3} can be obtained. If we assume a final radiation-induced defect density of 10^{13} cm^{-3}, it is possible to calculate an upper limit on the energetic flux that we can allow the sample to be exposed to during fabrication.

Consider an active region of the sample that is 1 cm^2 in area and extends from the surface into the sample to a depth equal

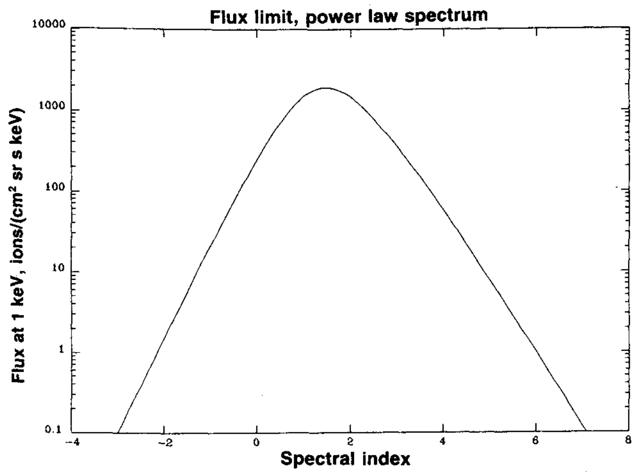

Fig. 1 The limiting flux of 1-keV ions that can be permitted and still obtain defect density one order of magnitude less than can be obtained on Earth is plotted vs spectral index for assumed power law spectra.

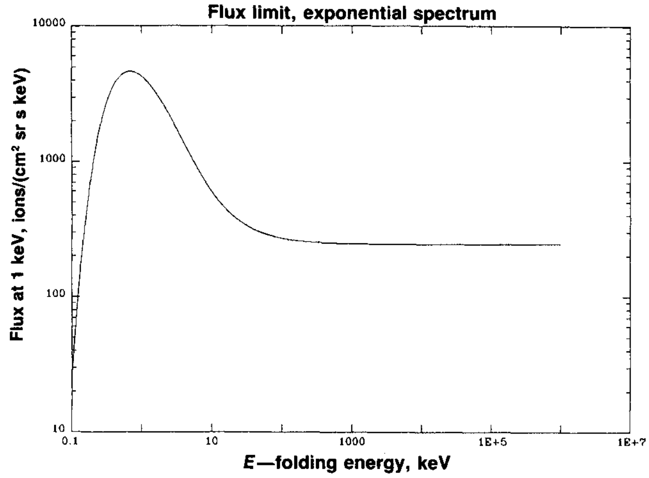

Fig. 2 The limiting flux of 1-keV ions is plotted vs *e*-folding energy for assumed exponential spectra.

to the particle projected range at a given particle energy. The time that this volume will be exposed to ions of this energy is equal to its depth divided by the growth rate of the sample, which we will assume to be 0.3 nm/s. The number of defects per unit volume produced in the sample by a given particle flux in the range 0.1–20 keV can be computed by integrating over the incoming particle distribution function weighted by the defect generation rate times one minus the annealing efficiency times the exposure time divided by the active volume. The defect generation rate has been assumed to be independent of incident ion mass for two reasons. First, at these energies it is a weak function of mass. Second, we do not expect ions heavier than O^+ to contribute significantly at Shuttle altitude; therefore using a rate that assumes pure oxygen will somewhat overestimate the damage, which is the conservative thing to do in designing the WSF. Integrating over the solid angle and leaving the energy integral explicit gives

$$N_D = \frac{10\pi}{v_s}\int_{0.1}^{20} E^{1/3}\frac{dN}{dE}\,dE \qquad (1)$$

In most cases in the magnetosphere, energetic particle spectra can be reasonably well-represented by either a power law or an exponential. For a desired defect density of 10^{13} cm^{-3}, Eq. (1) can be solved for an upper limit on the tolerable particle flux at 1 keV as a function of either spectral index or *e*-folding energy. The results of these calculations are shown in Figs. 1 and 2 for the power law and exponential cases, respectively. (The figures are labeled "ions" but they apply equally well to energetic neutral atoms.)

For the power law case, shown in Fig. 1, the best case situations occur for spectra that fall off as E^{-1} to E^{-2}, where fluxes of $\sim 10^3$ are tolerable. A flat flux, which has more particles at the more destructive higher energies, would have a limit more like 10^2. The exponential case, shown in Fig. 2, imposes a less stringent limit, $\sim 4 \times 10^3$, for *e*-folding energies near 1 keV. For the harder spectra that are more likely to be typical of ions and energetic neutrals at this latitude, a limit of $\sim 2 \times 10^2$ is imposed.

Consideration must also be given to the amount of damage that will be produced by the trapped ≥ 1 MeV protons of the inner radiation belt, since the flux of these particles is much greater than the flux of low-energy ions. In LLLEO, an integral flux of protons with energy > 1 MeV of 10^6 protons/(cm^2 s) is expected.[7] A Monte Carlo calculation made with the TRIM-88 code has shown that 1-MeV protons produce less than $\sim 10^{-6}$ displacement collisions per proton within the top 100 nm of a gallium arseum (GaAs) film. For the expected integral flux of protons, it is found that there will be one displacement collision/(cm^2 s) within the top 100 nm, prior to annealing. A typical mission duration and, therefore, total exposure time of 6×10^5 s gives a total of 6×10^5 displacement collisions/cm^2. In a film of 100-nm thickness, this number corresponds to a defect density of 6×10^{10} displacements/cm^3, which is significantly less than the desired maximum defect density. Therefore, the effect of the energetic inner-belt protons on epitaxial thin-film growth may be safely neglected.

Data

A review of the relevant data available in the literature will be presented in this section. These data can be conveniently grouped into three categories: trapped ions, transient ion acceleration events, and energetic neutral atom precipitation.

Trapped Ions

The presence of trapped ions in this energy, latitude, and altitude range has been a considerable surprise, inasmuch as charge exchange with thermal hydrogen reduces the lifetime of protons to less than the bounce time at altitudes below 400 km[8] and to less than the drift time at altitudes below 1000 km.[9] There have been three apparently different near-equatorial trapped ion populations reported. First, a low-energy trapped equatorial population has been seen at 600–1400 km altitude by several workers,[10-12] The cadmium sulfide (CdS) total deposited energy sensor on the Injun I spacecraft detected an energy flux of ions in excess of 50 ergs/(cm^2 s sr) in the energy range 0.5 keV $< E < 1$ MeV at altitudes of 893–1012 km.[10] Critics of this result have raised a number of unresolved questions regarding what was actually measured by the CdS detectors.[13] An experiment on the ISIS 1 spacecraft detected a flux of up to 10^9 "protons"/(cm^2 s sr keV) with energy 10 eV $< E < 410$ keV at an altitude of 1400 km.[12] These particles were assumed to be protons because the ISIS 1 ion spectrometer did not discriminate between ion species. It is entirely possible that they were primarily O^+ instead. Because of detector-background problems, this low-energy population is not often detected. Its sources, physical distribution, and temporal variations are all unknown at this time.

The second near-equatorial trapped population is found at and very close to the equator, $1.02 < L < 1.5$, and consists of ions with energies 10 keV $< E < 1.65$ MeV[8,9,11,14-17] This population is estimated to consist of protons and singly charged helium ions (He^+). However, the composition has not been as well measured as the energy spectrum. The source for this population is believed to be double charge exchange from the ring current.[9] The ring current is a permanent zonal current in the magnetosphere that is strongly intensified by magnetic storms. The primary carriers of this current are energetic protons and positive ions in the range $3 < L < 6$.[18] One of the main decay modes of the ring current are charge-exchange interactions, in which a ring current ion collides quasielastically with a cold neutral hydrogen atom in the geocorona and exchanges an electron in the process, producing a cold ion and an energetic neutral atom.[18-22] The charge-exchange interaction is, of course, a reversible process, so at low altitudes the energetic neutral flux from the ring current can be reionized and trapped on low altitude field lines.[9,23] The flux of this population has been found to be 10^8–10^9 ions/(cm^2 s sr) with energy of tens of electron volts to a few kiloelectron volts,[13] $\sim 10^6$–10^7 ions/(cm^2 s sr keV) for energy $0.04 < E < 8$keV,[11] 100 ions/(cm^2 s sr keV) at 12.4 keV,[8] an integral flux of 50 ions/(cm^2 s sr) for $E > 70$ keV,[16] ~ 1 ion/(cm^2 s sr keV) at 250 keV with an E^{-3} power law spectrum[9] and an integral flux of 7 ions/(cm^2 s sr) for $E > 500$ keV.[15] This second population may, in fact, be a downward extension of the population discussed in the previous paragraph. The observations of Galperin et al.[11] were made at a somewhat higher altitude than the others discussed in this paragraph and seem to indicate that the two populations are in fact continuous. On the other hand, Butenko et al.[16] found that this population appears to be confined to $L < 1.25$ and limited to the 1700-0500 magnetic local time (MLT) sector.

The third "trapped" population may, in fact, not be trapped but instead be the first of the transient acceleration events that will be presented. Two instruments on the International Sun-Earth Explorer 1 (ISEE-1) observed an intense flux of low-energy ions at low altitude near the equator that was continuously present in the 0300-1500 solar local time (LT) sector for a period of 6 months.[24] These ions had a narrow-peaked energy spectrum, with the peak in the range 10–20 keV. Both O^+ and H^+ were inferred to be present. These ions were mostly confined to the range $2 < L < 2.5$. However, the low-latitude wing of this distribution had an intensity of 10^3 ions/(cm^2 s sr keV) at $L = 1.59$. Williams and Frank[24] suggested that these ions were of ionospheric origin and had been locally accelerated by ion cyclotron waves.

Transient Ion Acceleration Events

In the vicinity of LLLEO, charge exchange will limit the lifetime of the ions of interest here to (much) less than a day. Therefore, it is expected that transient events are likely to be much more of a problem than trapped ions will be. As indicated in the next paragraph, the literature does not contain many reports of such events. However, this lack of data seems to be more a result of observational selection problems than of an actual absence of events. First, as a general rule, people are more interested in the auroral zone and polar cap than in the equatorial magnetosphere, and therefore, the region has not been studied carefully. Second, precipitating ion fluxes tend to be an order of magnitude less than electron fluxes, even in the auroral zone, and most ion detectors that have been flown in low Earth orbit (LEO) have had the same geometric factors as auroral zone electron detectors,[25] with the result that their threshold has been at least an order of magnitude above the flux levels of interest here. Third, the penetrating proton background problem mentioned previously has been a real barrier to progress.[26] Furthermore, there is positive evidence that suggests that LLLEO transient ion acceleration events are much more common than the literature indicates. The ion composition of the ring current at $E < 17$ keV and $L < 4$ is predominantly O^+,[27] and the dayside magnetosphere is found to "fill" rapidly with O^+ ions during the early phases of magnetic storms.[28] These points suggest that there is a local, low-altitude mechanism for extracting and accelerating ionospheric ions that operates on the low-latitude dayside during magnetic storms. Furthermore, Newell and Meng[29] have found that 100 eV to 1 keV ions are injected into at least $L = 2.4$ in the 0000-0830 LT sector by prolonged, intense substorm activity.

Despite the observational selection problems noted in the preceding paragraph, there have been several observations

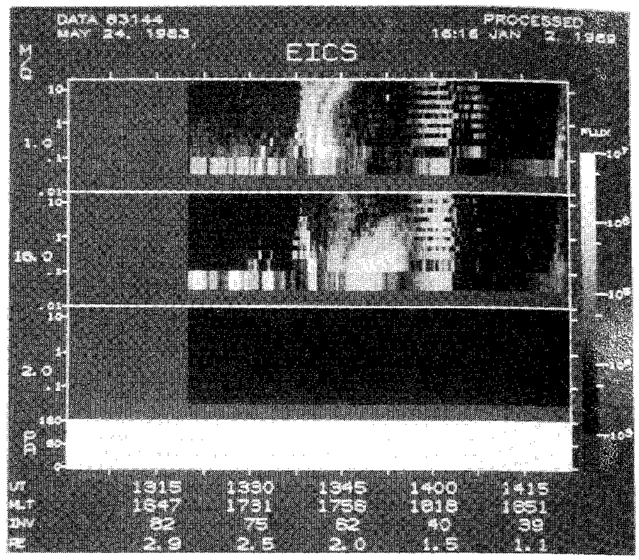

Fig. 3 Energetic ion composition spectrometer (EICS) data from the Dynamics Explorer (DE) spacecraft obtained on May 24, 1983.

of low-latitude ion acceleration events. During the December 12–13, 1972, magnetic storm, a sounding rocket at $L = 1.3$ saw upflowing 0.15–33 keV O^+ ion beams.[30] A sounding rocket launched into a spread-F event in the South Atlantic Anomaly observed a flux of O^+ ions of $\sim 2 \times 10^3$ ions/(cm^2 s sr keV) at 200 eV and 5 ions/(cm^2 s sr keV) at 1 keV.[31] The Kosmos-261 satellite observed an intense ion event at 220–270 km, in the range $1.6 < L < 3.4$ near midnight with a flux of $\sim 3 \times 10^7$–5×10^7 ions/(cm^2 s sr keV) for energies $0.04 < E < 8$ keV.[11] Recently, the energetic ion composition spectrometer (EICS) instrument on the Dynamics Explorer 1 (DE-1) spacecraft[32] has made several observations of low-latitude transient ion acceleration events. At least two reports of low-latitude O^+ fluxes of $\sim 10^6$–10^7 ions/(cm^2 s sr keV) at $L < 2.2$ have been published.[33,34] A third example is shown in Fig. 3. This figure shows energy and pitch angle spectrograms of H^+ (hydrogen ion or proton) and O^+ ions from May 24, 1983. The orbit passes through the low-altitude equatorial magnetosphere near local magnetic dusk. The spacecraft was at $L < 1.9$ for the interval 1357 to 1416 universal time (UT). Figure 3 shows that an intense isotropic flux of H^+ and O^+ ions with an intensity of 10^7 ions/(cm^2 s sr keV) was encountered during this time interval. No comprehensive, quantitative survey of these data has been made, so the frequency of such events is unknown.

The labels on the top, bottom, and right side of Fig. 3 identify the data segment, and the position of the DE-1 satellite at the time the data were acquired. The top three panels are energy spectrograms where the observed fluxes of hydrogen, oxygen, and singly charged helium ions averaged over all orientations for fixed time intervals in units of (cm^2 s sr keV)$^{-1}$ are encoded using the color bar on the right. The energy range displayed runs from 100 eV to 17 keV. The bottom eight gray-scale panels in the figure display angle-time spectrograms for hydrogen (middle four panels) and oxygen (bottom four panels). The top three panels in each of these sets presents data for 14 selected pitch-angle ranges integrated from 1–17 keV (top), 0.1–1 keV (second), and the lowest energy channel (third). These data are in units of (cm^2 s sr)$^{-1}$ and are also encoded according to the bar on the right. The bottom (fourth) panel in each set of angle time spectrograms is also from the lowest energy channel, but uses 12 selected angular ranges to cover the full 360-deg rotation of the satellite. The dotted white line in this panel indicates the direction of satellite motion. The other two panels display the background counting rate and a motion of the bulk motion of the plasma in the satellite spin plane perpendicular to the local magnetic field. The satellite was within the range $L < 1.9$ from 1357–1416 UT.

Energetic Neutral Atoms

An energetic neutral atom (ENA) will do the same amount of damage to a growing semiconductor as an ion of comparable energy will. As discussed previously, the ring current decays by charge exchange producing, as a byproduct, a substantial flux of energetic neutral atoms.[9,19] This model has been confirmed by observation of ring current ion lifetimes[20,35-37] by observations of the aurora equatorialis[22,23,38,39] and by using ENA fluxes to image the Earth and the ring current from distant spacecraft.[21,40] The Earth is expected to intercept 5-7% of the total ENA flux.[37] During a storm event in 1979, the ISEE-1 spacecraft, at a radial distance of $2.6R_E$ and an invariant latitude of 51.5 deg detected an ENA flux at 70 keV (assuming neutral atomic oxygen atoms) of 10^3 atoms/(cm^2 s sr keV). These observations were made during the main phase of an intense storm. During the later recovery phase, the ring current is expected to consist of He^+ ions and the ENA flux is expected to be significantly reduced.[20,35,36] It is certain that intense ENA fluxes will be present at LLLEO during the main phases of all magnetic storms. Unfortunately, the total fluence of ENA in the energy range of interest cannot be estimated without more data on the energy spectra of these particles.

Discussion

The fact that particle fluxes of unacceptable intensity will be present in the vicinity of the WSF during periods of enhanced geomagnetic activity could be taken to indicate that suitable shielding must be placed around the working volume of the WSF in the default baseline design. However, "suitable shielding" is undesirable for several reasons, including the need to maximize the effective vacuum pumping rate of the system and the difficulty of properly outgassing the shield material and thus reaching the desired levels of vacuum. The difficulty with not shielding is that we do not know what the quiet-time background fluxes are and we also do not know what percent of the time the flux levels are unacceptable. We believe, therefore, that an informed design decision requires more information about the background flux in 0.1-20 keV energy range than is now available. If the quiet-time background flux is low enough for a large enough percentage of the time, the optimum shielding strategy will be to cover the substrate carousel only during periods when the radiation background is too high. Implementation of this strategy will require a real-time radiation monitor on the WSF.

Successful detection of particle fluxes at the intensity levels that threaten the proposed WSF experiments is a formidable technical problem. The major problem is the presence of the megaelectron volt proton background trapped population of the inner zone. The required detector must be able to detect fluxes of 10^2 ions/(cm^2 s sr keV) in real time. A detector with a geometric factor of ~ 1 cm^2 sr and a background rejection ratio of 10^5 will be adequate. Fortunately, detailed pitch-angle information is not required. A maximum of five detectors with ~ 45 deg full width at half-maximum (FWHM) angular resolution will be adequate to define the shielding needs of the epitaxial growth facilities on WSF. Detectors with the required geometric factor have recently been flown on sounding rockets.[41] Adding the required active anticoincidence shielding and maximizing the scattering suppression capabilities of the collimators has only been attempted once, with some success.[8]

Flight of monitoring instruments on the WSF proof-of-concept flights alone will not suffice to answer the production facility design questions posed in this paper. The reasons involve the time scales that control geomagnetic activity. The proof-of-concept flights will last about a week each with six flights being proposed. Major geomagnetic storms produce ring current intensifications and associated low-latitude radiation increases that typically last 2-3 days at a rate of one or two storms per month. A mere 6 weeks of observing cannot suffice to determine background statistics accurately enough to design a full-scale production facility. Thus, a long-term survey by a suitable, small, unmanned satellite instrument would seem to be required.

Conclusions

The epitaxial thin-film semiconductor devices to be grown on WSF are expected to be subject to undesirable levels of radiation damage if the flux of ions and energetic neutrals with energy $0.1 < E < 20$ keV exceeds $\sim 10^2$-10^3 p/(cm^2 s sr keV) where p = particles. The available data from LLLEO on particles in this energy range have been reviewed. The data, in general, are scanty and scattered. We cannot, at this time, determine if the quiet-time trapped fluxes are intense enough to require that shielding be provided. A good set of monitoring instruments is therefore an absolute requirement for the WSF proof-of-concept flight. Even if it is concluded that shielding is not required for quiet-time operations, there are enough transient events that are certain to occur and exceed the desired threshold to make real-time monitoring during production flights a requirement. Finally, since the WSF proof-of-concept flights will only be on orbit a week at a time and since the geomagnetic environment is a very variable and dynamic place, it seems that a statistically adequate answer to the shielding question cannot be obtained from the WSF flights alone. A suitable low-latitude Explorer class unmanned spacecraft mission would seem to be required to solve this problem properly.

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