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L. Varga and E. Horvath

DEFENCE RESEARCH ESTABLISHMENT OTTAWA
TECHNICAL NOTE 98-008

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Space Systems and Technology Section

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ABSTRACT

Kapton films were irradiated by high energy protons and alpha particles at the Tandem Accelerator Laboratory at McMaster University. A complementary Monte Carlo simulation has also been carried out and the results compared. The correlated results of the two investigations indicate that the surface damage in Kapton materials in space is predominantly caused by the low energy ions.

RÉSUMÉ

Des films Kapton ont été irradiés avec des protons à haute énergie et des particules alpha au Tandem Accelerator Laboratory à l' Universitée McMaster. Une simulation Monte Carlo complémentaire a aussi été exécutée et les résultats ont été comparés. Les résultats correllés des deux enquêtes indiquent que le dommage de surface dans les materiaux Kapton dans l'espace est causé principalement par les ions de basse énergie.

EXECUTIVE SUMMARY

Polymer materials, with their light weight and optimal electrical and mechanical properties are widely utilised in space-based applications. Kapton (polypyromellitimide), for example, is a material used as an electrical insulator, thermal blanket layer, substrate for solar cell arrays, and surface coating.

Currently, in-flight experimentation for the qualification of materials requires extensive preparation, the results are returned after considerable delay, and the space environment during the testing must be well known. This testing procedure often does not constitute a feasible way to evaluate materials, especially for a project under development.

Performance of materials destined for space applications can, however, be evaluated in laboratory tests. Laboratory-based irradiations of polymer materials provide valuable information on the effect of the space environment radiation although the lack of sufficient synergism in a laboratory set up constitutes a drawback. The advantage of laboratory testing is in parameter control and measurement.

This work represents the results of the radiation tests performed on Kapton-H samples using protons and alpha particles to determine their effect on this material. The experimental results are explained in view of Monte Carlo simulation results.

CONTENTS

1. INTRODUCTION

Laboratory experiments, computer modelling, and space-based (ex. LDEF, CRESS) experiments conducted on the subject of interactions between the natural space environment and a spacecraft and its components have revealed that irreversible damage can occur to electronic devices and materials[1] on board orbiting spacecraft. Effects of the space radiation environment on spacecraft and their components is a subject of intense investigation. As a result, a significant body of knowledge about the deleterious effects the space environment has on spacecraft interaction is emerging.

We have carried out high energy ion beam irradiation experiments and Monte Carlo ion transport simulations using Kapton polymer as the target. Kapton (polypyromellitimide) has been selected as a specimen because it is widely used in space applications (thermal blankets, solar arrays, coatings, etc.) and the aim of this work is to investigate the erosion damage caused by the space radiation environment on Kapton polymers. This work is one of a series of results from the on-going investigation at DREO aiming at studying the effects of the space environment on electronic devices and dielectric materials.

2. SPACE RADIATION ENVIRONMENT

The natural space radiation environment is known to consist of electromagnetic radiation over a large range of wavelengths and corpuscular radiation such as electrons, protons, and heavy ions of various energies and ionization states. Corpuscular radiation comes from several sources, namely: trapped protons, heavy ions, and electrons due to the Earth's magnetic field; protons and heavy ions from galactic cosmic rays; and protons and heavy ions from solar flares.

Spacecraft at Low Earth Orbits (LEO) with small orbit inclination angles will be largely shielded from the effects of galactic cosmic rays and solar flare particles. The exposure to cosmic rays of galactic and solar origin, however, increases with the inclination angle of the orbit. Although Low Earth Orbits are situated below the general population of the trapped radiation, the trapped proton component intercepts the orbit in the vicinity of the South Atlantic Anomaly (SAA). NASA's standard trapped proton model (AP8) shows that the flux of trapped protons at LEO is very localized due to the limited extent of the SAA. This flux will also be affected by the inclination angle and the altitude of the orbit (Figure 1).

The presence of trapped He and heavy ions with $Z>=4$ in Earth's radiation belts has been confirmed from numerous observations[2,3,4,5] but has been receiving much less attention than the population of protons and electrons. Equatorial observation (Explorer 45)[6] had indicated that the flux ratio of helium to proton (J_{He} / J_H) varies from 0.1 to 1e-3

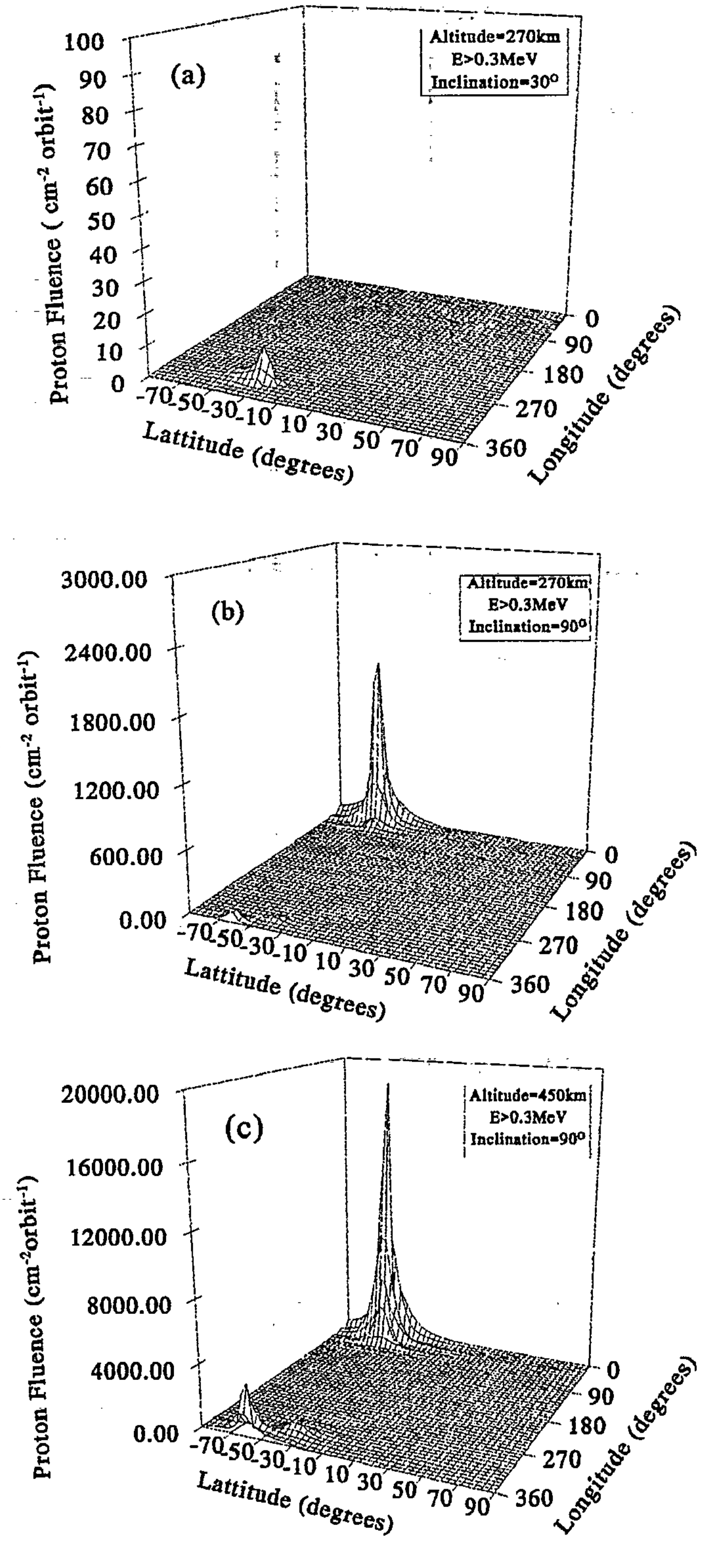

Figure 1. Altitude and inclination angle effects on observed fluence of protons at LEO.

depending on energy, pitch angle, and L shell value. A population study of other ions such as carbon and oxygen indicate that J_C/J_{He} and J_C/J_O ratios are about 0.025 and 0.33 respectively. These ratios correlate with the same population ratios as in the solar wind.

3. RADIATION TESTS

Simulation of the effect of the space radiation environment on Kapton-H film samples was carried out at the Tandem Accelerator Laboratory at McMaster University using protons and alpha particles. The samples tested were 7mm ±20% squares having thicknesses of 0.1mm. Tables 1 and 2 summarize the ion energies, angles of incidence, and fluence levels delivered to the samples. The experimental arrangements for the samples irradiation are schematically illustrated in Figure 2. For the alpha particles, the "scattering" mode setting (Figure 2a) has been employed. In this setup, before the beam enters the sample chamber it undergoes Rutherford scattering. After the initial calibration by the detector for energy and flux, the samples are rotated into the slit and exposed for the specific time needed to obtain the required fluences. The "In-line" setup, shown in Figure 2b, was employed for the proton beam case (direct beam exposure). In both cases of the experimental setup, the specimen holder design allows multiple specimen insertion into the irradiation chamber as well as allowing a change in the beam incidence angles on the specimens without the need for braking the vacuum (approximately 10^{-5} Torr). The irradiation experiments were carried out at a temperature of 298 degrees K. The damage to specimens was measured by a weight loss technique on a microscale capable of ±10 microgram accuracy.

Table 1. Experimental parameters for the proton beam case

Specimen	Energy (MeV)	Approach Angle(°)	Fluence (particles cm^{-2})
1	3	0	4.38E8
2	3	0	9.10E8
3	3	0	5.25E9
4	3	60	4.40E8
5	3	60	9.10E8
6	3	60	5.39E9
7	6	0	5.00E8
8	6	0	1.09E9
9	6	0	4.94E9
10	6	60	4.94E8
11	6	60	9.99E8
12	6	60	5.05E9

Table 2. Experimental parameters for the alpha beam case

Specimen	Energy (MeV)	Approach Angle(°)	Fluence (particles cm^{-2})
1	3	0	5.01E5
2	3	0	9.98E5
3	3	0	5.02E6
4	3	60	5.05E5
5	3	60	9.95E5
6	3	60	4.99E6
7	6	0	5.00E5
8	6	0	1.00E6
9	6	0	5.01E6
10	6	60	5.00E5
11	6	60	1.05E6
12	6	60	5.00E6

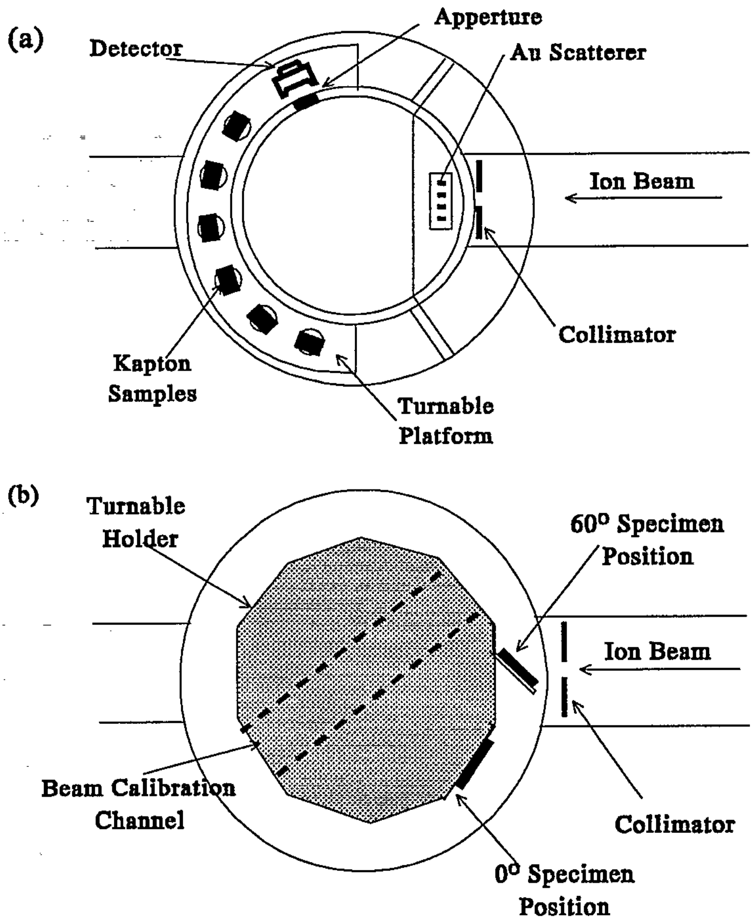

Figure 2. Schematic diagram of the experimental setup: (a) "Scattering mode", (b) "In-line" mode.

4. EXPERIMENTAL RESULTS

The experimental results were subjected to standard hypothesis testing for paired samples using

$$t = \frac{dave}{(\frac{sd}{\sqrt{n}})}$$

where t is a variable with t-distribution, s_d is the sample variance, d_{ave} is the average weight difference between irradiated and nonirradiated samples, and n is the number of specimens used. The results were analyzed to test the significance in weight difference of the specimens before and after the irradiation using a 95% confidence level and 11 degrees of freedom. The decision of change/no change in the masses of the specimens was based on rejection/acceptance of the null hypothesis. Scale reading error, estimated at $\pm 10 \mu g$ (parallax effect and vibration), has been incorporated into the results (error bars) via the error propagation method. The following summarizes the experimental results:

Ion Mass	Significant weight reduction observed in alpha-irradiated specimens. No change in the weight of proton-irradiated specimens (Figure 3).
Beam Energy	Changing the beam energy from 3 MeV to 6 MeV produced no change in the weights of the specimens, either in the alpha or proton irradiated group (Figure 4a and 4b).
Angle of Incidence	Changing the angle of beam incidence from 0° to 60° had no detectable effect on the mass change of samples in either the alpha or proton irradiated groups (Figure 5a and 5b).
Beam Fluence	Changing the fluence delivered to the specimens had no detectable effect on their mass.

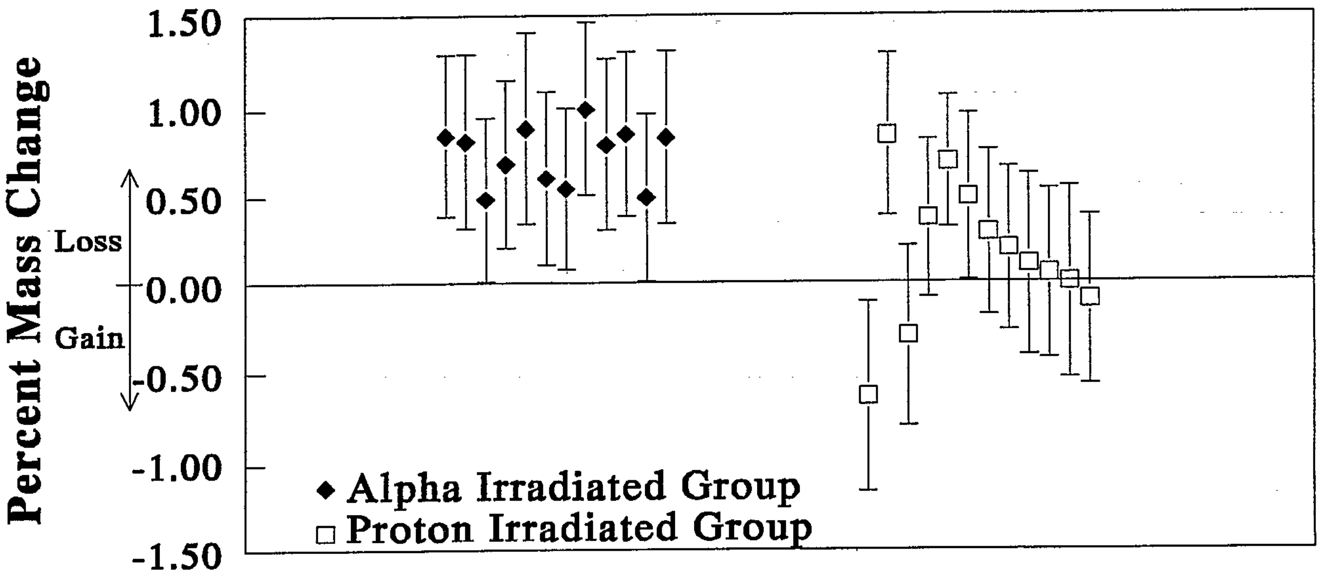

Figure 3. Measured mass change of the specimens from the alpha-irradiated and proton-irradiated groups

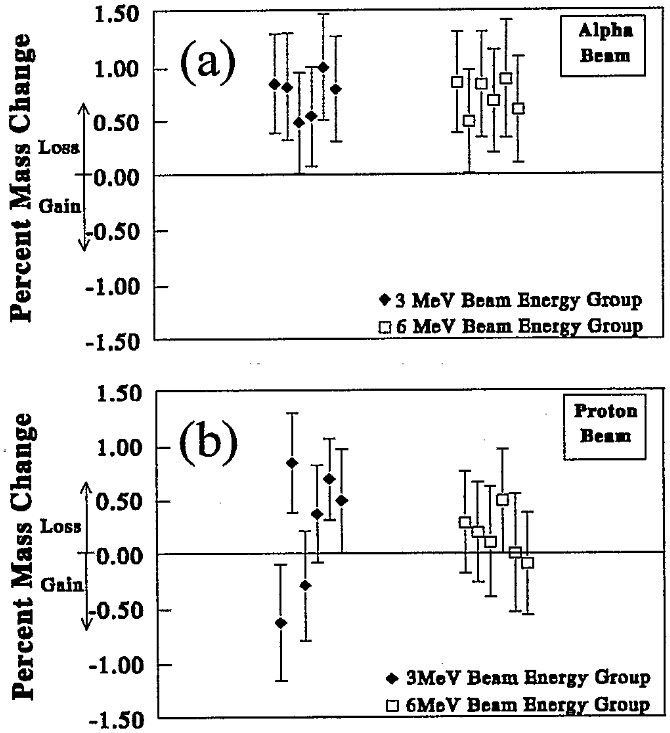

Figure 4. Energy effect on the mass change of Kapton film specimens irradiated by (a) alpha, and (b) proton particles.

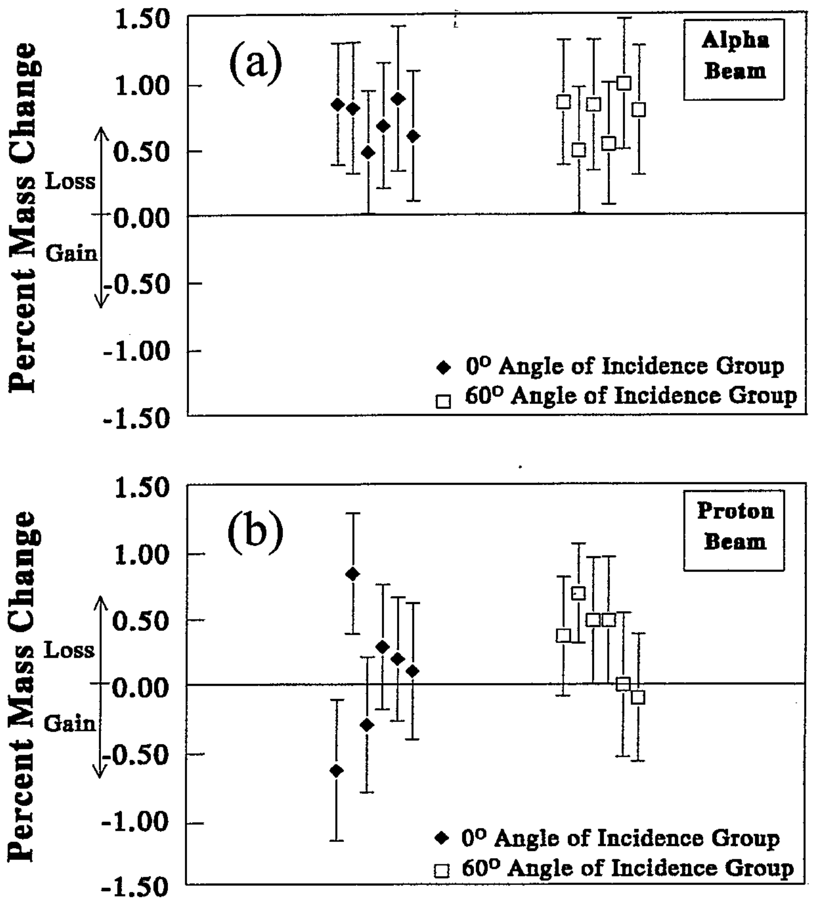

Figure 5. Beam angle of incidence effect on mass loss in Kapton film specimens for (a) alpha, and (b) proton particles

5. COMPUTER MODELLING AND DISCUSSION

TRIM Monte Carlo code simulations have been carried out in order to gain some insight regarding the outcome of the experiment. The code was modelled the propagation of protons, alpha particles, and oxygen ions through the Kapton material.

The effect of the ion mass on sputtering yield can be inferred from Figure 6 showing the tracks of ions and displaced target atoms for 10 keV protons, alpha particles and oxygen ions. The simulated number of incident ions in each case was 1000. High sputtering yield requires extensive collision cascades to occur at, or very near, the surface of the target. We have selected the first 100 Angstroms layer of the target to observe the density of tracks generated by recoils or displaced target atoms at the surface of the target. Because of such extensive collision cascades, oxygen ions have a higher sputtering yield than alpha particles or protons. The simulated sputtering yield results for alpha particles, oxygen ions, and protons are summarized in Figure 7.

Figure 7 also shows that the sputtering yield for a given ion is energy dependent as shown over the energy range of 100 eV to 6 MeV. The location of the maximum sputtering yield for both protons and alpha particles in the Kapton material occurred at an energy just slightly below 1 keV, which is well below the ion energies delivered by the accelerator. At 3 MeV and above, the sputtering yields become negligible. For the oxygen ion, the sputtering yield peaked at about 5 keV. The simulation results here offer a plausible explanation for the observed lack of target material loss in both alpha and proton beam cases.

The dependence of the sputtering yield on the ion incidence angle was modelled for 0° and 60° angles. The results are presented in Figure 8 as ratios of sputtering yield at 60° to sputtering yield at 0°, and also as a function of energy. The sputtering yield ratios for both ions at 3 MeV and 6 MeV is approximately equal to unity which supports the experimental observation summarized in section 4.

6. CONCLUSION

TRIM simulations have indicated that the damage cross-section for Kapton films increases with the mass of the ion and that the maximum damage cross-section is located below the energy of 10 keV. The small cross-section for sputtering at energies in the MeV range supports the experimentally observed lack of damage in Kapton specimens. Both the experimental and the simulation results indicate that damage to Kapton materials exposed to the space environment will be generated by the low energy ions.

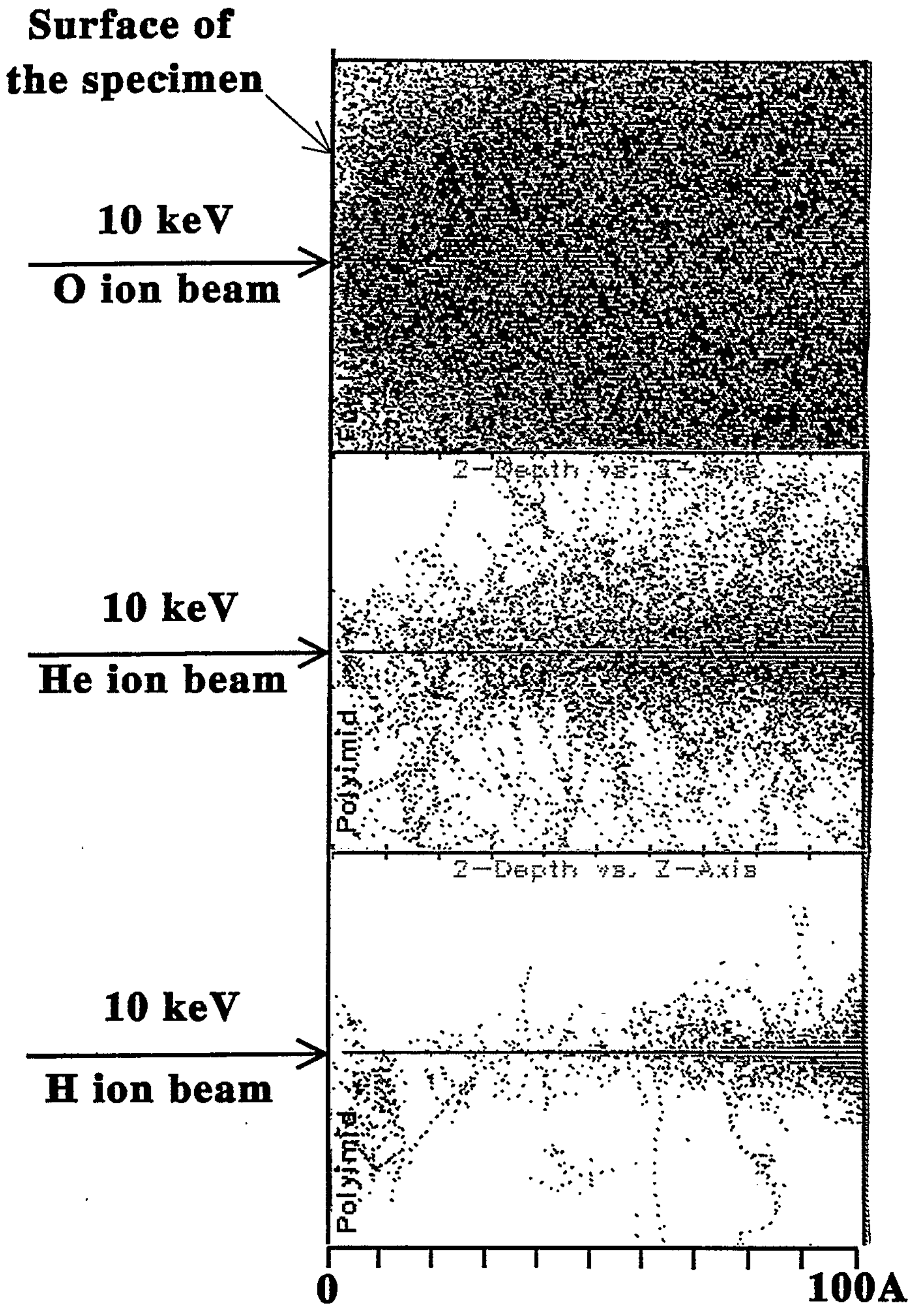

Figure 6. Subsurface collision cascades for protons, alpha particles, and oxygen ions.

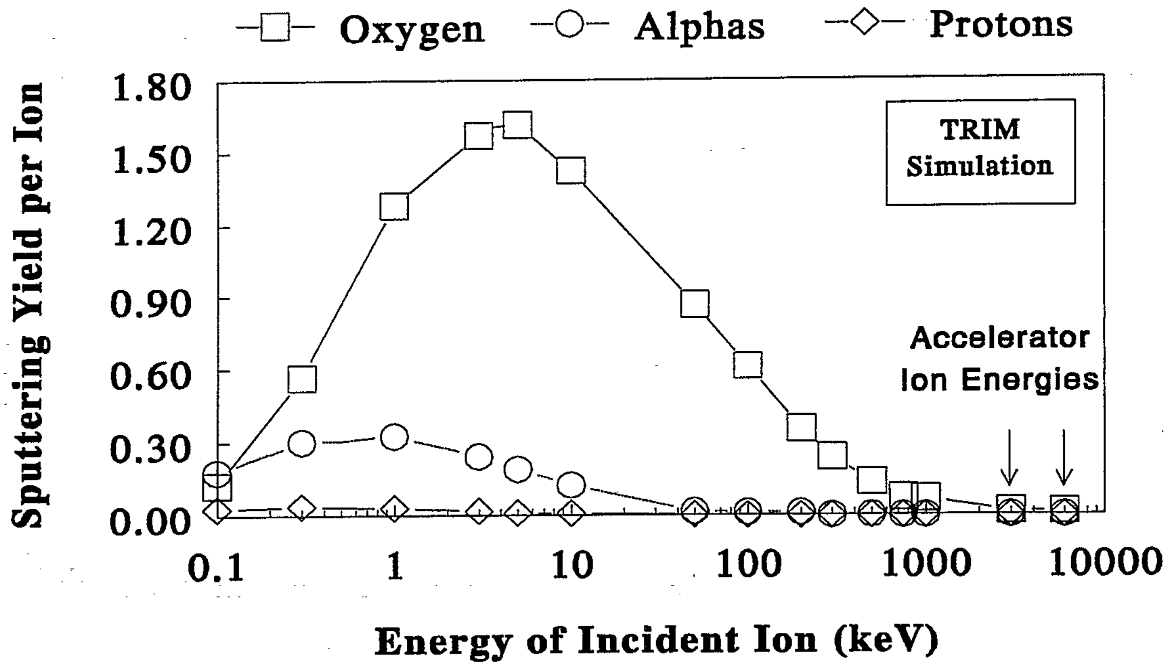

Figure 7. Effect of ion mass on the sputtering yield in Kapton films

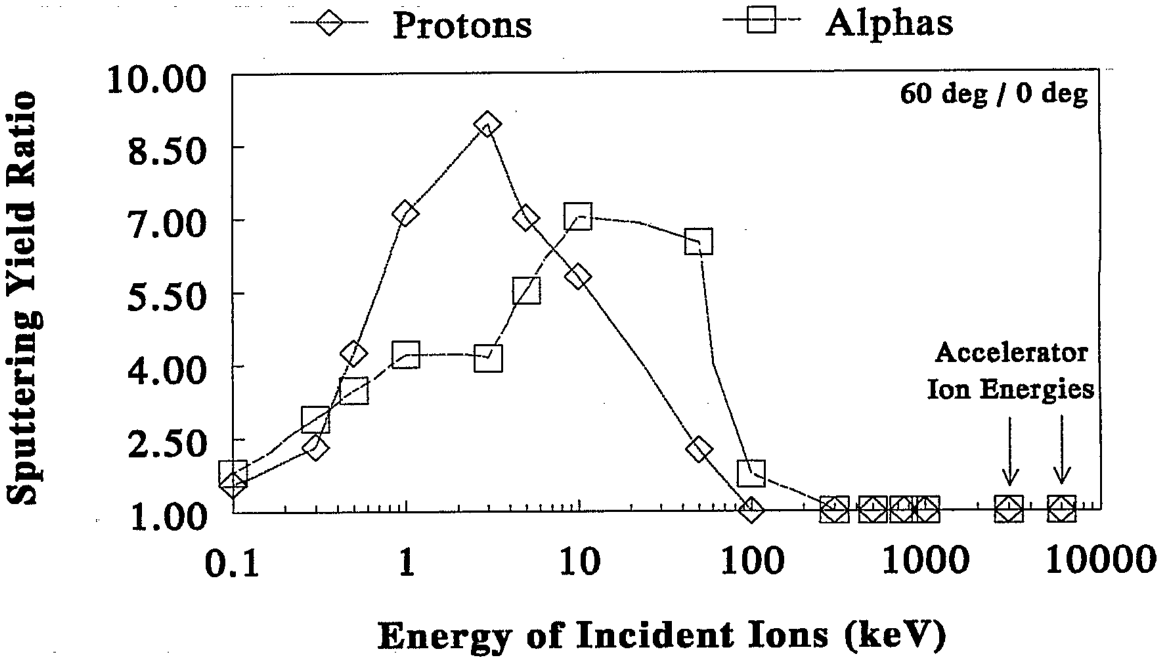

Figure 8. Effect of ion beam angle of incidence on the sputtering yield in Kapton films

7. ACKNOWLEDGEMENTS

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