 modification of organic polymers with vacuum ultraviolet radiation from inert gas plasmas rotating in a magnetic field.

Jian-Xin Chen

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MODIFICATION OF ORGANIC POLYMERS WITH VACUUM ULTRAVIOLET RADIATION FROM INERT GAS PLASMAS ROTATING IN A MAGNETIC FIELD

JIAN-XIN CHEN

NOVEMBER, 1990

THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

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MODIFICATION OF ORGANIC POLYMERS WITH VACUUM ULTRAVIOLET RADIATION FROM INERT GAS PLASMAS ROTATING IN A MAGNETIC FIELD

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November, 1990
ABSTRACT

DC arc plasmas containing He and Ar, which were made to rotate by the application of a magnetic field, were used for generating vacuum UV light (VUV) to modify polymer surfaces. Polymers such as poly(tetrafluoroethylene) (PTFE), fluorinated ethylene propylene copolymer (FEP), polyimide (PI), UPLEX-S and UPLEX-R were modified with and without optical filters for different exposure times. PTFE was also exposed to helium and argon arc plasmas at different exposure temperatures. After the treatment, the polymer films were measured by weight loss, contact angle and Scanning Electron Microscopy (SEM). Copper was sputter deposited onto some of the treated samples and the adhesion between copper and polymer film was measured using a peel test.
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1.0 INTRODUCTION

Helium or argon arc plasma can alter the surface of organic polymers. Reactive metastables, ions, and radiation can each induce main chain scission, crosslinking, and/or changes in elemental composition of polymer surfaces [1]. The extent of the modification is frequently measured by different methods such as contact angle, weight loss, profilometer, Scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS), etc. to determine the adhesion or bondability of modified polymer surfaces with other materials deposited on them [2]. This paper will report on the modification of polymers with vacuum UV (VUV) radiation and the likelihood that such modification will improve the adhesion of copper onto the polymers.

Surface treatment by methods such as corona discharge and chemical etching have been shown [3] to produce crosslinking on polyethylene surfaces and strong joints. Chemical modification occurs at the etched surface in a film whose thickness is limited to a few thousands of angstroms or less [4,5].

R. H. Hansen and coworkers [6, 7, 8] observed that O atom producing plasmas improved wetting of polymer surfaces and the adhesion between polymer surfaces. The bombardment of PTFE with He+ in radio-frequency plasmas resulted in CASING (Crosslinking by Activated Species of INert Gases) that increased bondability to PTFE. Cheeks and Ruoff [9] bombarded various polymers, including PTFE, with He ions which served to defluorinate the surface.
J. H. Brannon et al. [10] exposed Kapton (Polyimide) to radiation from an excimer laser in vacuum and air. They found that O2 played no direct role in the etch rate, but it made the combustion of heated organic species occur rapidly. The black soot of high molecular weight hydrocarbons which existed in vacuum etching environment did not form in the presence of O2.

H. Yasuda [11] and Pauling [12] suggested that introduction of polar atoms such as fluorine, oxygen, nitrogen, and chlorine, onto the surface of a nonpolar material should be expected to enhance its wetting and adhesion.

Helium and argon metastables have excitation energies (19.8 and 11.5 eV, respectively ) which are greater than some polymer ionization energies. Simultaneous exposure to He metastables and vacuum ultraviolet (VUV) radiation (12 eV to 54 eV ) shows a rapid and then gradual reduction in the value of the receding contact angle of water with exposure time for untreated films of polytetrafluoroethylene (PTFE) and polyethylene (PE) (103° and 93°, respectively ) to a minimum of 20° [13].

J. Peeling et al. [14] exposed PET to UV radiation at wavelength 254 nm. The exposed surface was measured by contact angle and analyzed by XPS . They found that photooxidation caused main chain scission which produced low molecular weight polar fragments at the surface. The contact angle was reduced after treatment.

S. H. Lee [15] obtained results of contact angle measurements on rf-sputtered PMMA for both nonirradiated and UV-irradiated (253.7 nm) surfaces. The initial wetting angle decreased from 140° for the
nonirradiated sample to 104° for sample irradiated for 45 min. and then
increased to 123.5° for sample irradiated for 60 min. On the other hand,
they found that the size of the water drop decreased with time probably
because the water penetrated into the micropores developed by the
extraction of the photooxidation products and by the degradation of the
polymer matrix.

UV radiation from low pressure mercury lamps also have been
shown to reduce the water contact angle for poly( methyl vinyl ketone ) and
several silicone containing polymers [16,17] in air due to photo-oxidation
of the surface.

C. A. L. Westerdahl et al. [18] observed that treatment in low-
temperature radiofrequency excited helium plasma for one hour reduced the
water contact angle of fluorinated ethylene propylene copolymer (FEP)
from 103° to 83°.

Exposure of PTFE to Mg Kα x-ray radiation (1.0 nm) produced a
damaged layer of crosslinked or branched PTFE which showed a reduced
hexadecane contact angle of 26° compared to 44° for the unexposed
polymer [19].

V. Momose and co-workers [20] used XPS and electron spin
resonance (ESR) spectroscopy to study the surfaces of polyamidoimide and
polyimide (PI) treated with UV radiation (253.7 nm) in O2, O2 + N2, air
atmospheres and vacuum. Free radicals were found in all cases and their
concentrations decayed more rapidly in oxygen atmospheres than in
vacuum.
E. M. Liston et al. [21] showed that plasmas emit various amounts of VUV light (at wavelengths less than 180 nm). The materials being processed are immersed in the light producing medium, the plasma, with no intervening windows. Data were presented to show that the VUV energy is absorbed in the top few molecular layers (10-60 nm) of the surface of polymers and that there is sufficient photon energy to break any organic bond in the surface. The report also showed that VUV radiation also can cause as much as 60% of the rate of surface reactions that are caused by complete immersion in the plasma.

K. A. Valiev et al. [22] indicated that VUV light with wavelengths 115-125 nm, penetrates into PMMA to a maximum depth of about 30-50 nm. The photo-modification made the polymer surface reduce the molecular weight to volatile compounds. The VUV etching of the polymer film was found to be layer-by-layer.

W. M. Alvino [23] exposed polyimide (PI) to UV light, \(\lambda_0 = 280-400\) nm, for thousands of hours. The polymer was found to be sensitive to UV light and the sensitivity was enhanced in the presence of moisture. The strength and elongation of the polymer decreased immediately after exposure. The benzophenone group in PI could possibly impart some resistance in the polymer film to UV radiation in dry environment. They also indicated that type H polyimide film possesses good resistance to UV light [24].

J. O. Chio and coworkers [25] exposed poly(methylmethacrylate) (PMMA) to deep UV, X-ray, electron beam and proton beam irradiations. They observed that more main chain scission of PMMA was caused by
proton beam than by e-beam. The X-ray is the best radiation source to cause main chain scission with fewer ester groups removed.

M. Hudis et al. [26] indicated that UV radiation at 253.7 nm doesn't produce much crosslinking, but the effective wavelengths for polyethylene crosslinking occurs below 190 nm.

Srinivasan et al. [27] suggested that photochemical decomposition is the main effect on polyimide when the polymer film was exposed to UV laser at wavelengths 248 or 308 nm. UV laser ablation of polyimide was shown to be a multiphoton process.

PMMA has its maximum absorption at about 215 nm, and it does not have any significant absorption at wavelengths longer than 250 nm [28]. In contrast, polystyrene has moderate UV-absorption at wavelengths longer than 250 nm due to its aromatic component [29]. Polyimide films have relatively strong UV-absorption even at 300 nm [30]. When a small amount of pyrene was added on PMMA as a dopant, photoetching of PMMA occurred at 308 nm [31].

A. L. Ruoff et al. [32] studied the adhesion between copper and polyimide which was etched by reactive ion-beam. After etching, they found that the roughness of the polymer surface increased. Oxygen-reactive ion-beam etching oxygenated the PI and decreased its carbon and nitrogen concentration. The peel strength of Cu on the PI film surface was increased 25 times from 2.5±0.3 g/mm (unmodified) to 70±5 g/mm (5 minute modified). However, excessive exposure to oxygen-reactive ion-beam etching resulted in a low peel strength because of the failure at the "root"s of the thin, long "blades" of the resulting grass-like surface structure of
the PI film. Surface oxidation is often used to increase the surface energy of polymers and to improve adhesion, wettability, and printability [33].

H. Yasuda et al. [34] indicated that nearly all polymers lost weight when exposed to helium plasma at 100 μm Hg pressure and 30 W power. The rate of weight loss was proportional to the time of exposure and somewhat dependent on the type of gas used. The weight loss was also dependent on the discharge power.

Although x-ray and UV effects on polymers have been well studied, especially for lithographic purposes [30, 35], there have been few investigations of the effects of VUV radiation emitted from plasma on polymers [36, 37]. VUV radiation has been shown to cause: (1) cleaning and crosslinking of polymer surfaces [26], (2) fluorination of polymers [38], (3) generation of free radicals in polymers as observed by ESR [39], (4) effective photoetching of PMMA (~10 nm/min. for λ ≥ 115 nm) [22], (5) photoelectron emission accompanying optical absorption in the wavelength region from 20 to 100 nm for polystyrene and fluoroelastomer F32L [40], (6) chemical modification, as observed by XPS, of poly(ethylene tetrafluoroethylene) (λ ≤ 160 nm) and PET (λ ≥ 160 nm) [41], and (7) cis-trans isomerization and loss of unsaturation for several unsaturated polymers, including polybutadienes and polyisoprenes, involving both ionized and excited states of the polymers [42-45]. Egitto and Matienzo [13] exposed PTFE and PE to filtered radiation downstream from a helium microwave plasma and detected modification, as observed by deionized water contact angle measurements and XPS analysis, with photons having energies greater than the first ionization potentials of PTFE (9.93 to 11.28
eV) and PE (7.75 to 9.19 eV). XPS analysis revealed extensive defluorination of the surface of PTFE while PE surfaces displayed enrichment in C-O bonding, presumably formed from the reaction of surface sites with oxygen upon exposure to air.

The low pressure (2.4 x 10² Pa) radiation sources used in the above experiments are primarily VUV line sources; however, there are significant outputs in the ultraviolet and visible regions [46]. For helium and argon, the neutral atom resonance lines are at HeI (~58.4 nm) and ArI (~104.8 nm, 106.7 nm) while for the singly ionized species they are HeII (30.4 nm) and ArII (~92.0 nm, 93.2 nm) [46]. In the high pressure (6.7 x 10⁴ Pa) source used in the experiments reported in this paper, a significant contribution of radiation from the continuum spectra of the rear gas molecules is expected to be superimposed on the line spectra. The most intense ranges of these continua are He₂* 58-110 nm and Ar₂* 105-155 nm [46].

In this paper, some organic polymer films, that are important in electronic packaging applications, such as polytetrafluoroethylene (PTFE), fluorinated ethylene-propylene copolymer (FEP), polyimide (PI), UPILEX-S and UPILEX-R were modified with radiation from high pressure inert gas plasmas rotating in a magnetic field. To investigate the role of wavelength of photon energy, the films were covered with LiF and fused silica optical filters which had different cut-off wavelengths. Modification was monitored by measurements of distilled water contact angle, weight loss, surface roughness, and atom composition on the top 3 to 5 nm of the exposed film as a function of: exposure time, temperature, polymer
structure, inert gas (He or Ar), and optical filter. Copper was sputter deposited onto some of the treated samples and the adhesion between copper and the modified polymer film was measured by a peel test.
2.0 EXPERIMENTAL

2.1 Rotating Arc Apparatus

2.1.1 Reaction Chamber

Figure (1) shows the view of the experimental apparatus from the front. The reaction chamber was the Pyrex tube which was placed on a aluminum plate. On the Al base plate, there are vacuum connections for the vacuum outlet, gas inlet, thermocouple, cathode feed through and pressure gauge. The anode feed through is located on the top plate. Two rubber gaskets were used as seals between the tube and the plates. Figure (2) is the schematic diagram of rotating arc experiment.

2.1.2 Electrode

The arc electrodes were a graphite cathode rod (Bay Carbon Inc.) positioned coaxially in a graphite anode tube (Bay Carbon Inc.) (Figure (3)). The sharpened end of the graphite cathode rod and the end of graphite anode were eroded away while the DC arc rotated at the end of the anode tube. Therefore, the graphite cathode rod and graphite anode tube were replaced after every 10 minutes of use.
Figure (1). Reaction chamber
Py --- Pyrex Glass Pipe
R   --- Anode Ring Support
AN   --- Anode Feed through
CA   --- Cathode Feed through
S   --- Substrate Holder
M   --- Magnets
G   --- Gas Inlet
TC   --- Thermocouple
P   --- Pressure Gauge
V   --- Vacuum feed through
Figure(2). Schematic diagram of rotating arc experiment
M  --- Magnetic coils

RC  --- Reaction Chamber

PS1  --- Arc Power Supply  (MFG. Spectro Equip. Inc.)

PS2  --- Magnetic Coils Power Supply (AL 7500 power supply, The Superior Electric Co.)

TC  --- Thermocouple  (Omega Corporation, K-type, -200 to 1250 °C)

P  --- Pressure Gauge  (Matheson)

V1  --- Vent Valve

V2  --- Throttle Valve

RP  --- Vacuum Pump  (Welch Duo-Sela Vacuum Pump 1405, Sargent-Welch Scientific Co.)

FM  --- Gas Flow Rate Meter  (Matheson 604 rotameter flowmeter)
Figure (3). Anode and Cathode
2.1.3 Thermocouple Meter and Gas Flow Rate

The thermocouple with the same extension wire (Omega Co., K-Type, -200 to 1250 °C) was attached to the surface of aluminum ring next to polymer, and the temperature was measured at different time intervals during the exposure to the arc plasma.

The gas flow rate was determined by measuring the time to displace 1 liter of water at barometric pressure. The gas flow rate at chamber pressure 500 torr, which we used in all experiments, was determined to be 0.082 l/s.

2.1.4 The Power Supplies of Arc and Magnetic Coils

In order to produce a homogeneous source of radiation at the polymer substrate, the arc was made to rotate at the edge of the anode by the application of a magnetic field outside of the vacuum chamber. The two magnetic coils (16 cm radius) were separated by 34 cm and were constructed from 18 gauge copper wire wrapped around an aluminum frame. The coils were wired in parallel with an Alpha AL 7500 DC power supply so that their magnetic fields were in the same direction. By adjusting the current output of the magnetic power supply, the magnetic field strength was varied. Typically, a 3A current was used in all experiments reported here. As determined with a calibrated Dyna-Empire, Inc. Model 888 gaussmeter, the magnetic field strength at the arc was 94
gauss which produced about a 130 Hz plasma rotation frequency [47].

The arc rotated on the tip of the graphite cathode around the graphite tube that was supplied with 7 amps of current of a DC power supply (Jarrell-Ash Div. DC-Arc). A constant voltage of 110 V, grounded of anode and 110 V of cathode, was maintained across the electrodes for all experiments.

2.2 Experimental Conditions

2.2.1 Polymers

Poly(tetrafluoroethylene) (PTFE) (Dupont), fluorinated ethylene-propylene copolymer (FEP), Kapton-H (polyimide) (PI) (Dupont), UPILEX-S (ICI), and UPILEX-R (ICI) were used as samples. Table 1 shows the structures and physical properties of the polymer films. The samples were mounted on a substrate holder (Figure (4)) which was placed 5 cm from the face of the arc electrode.

2.2.2 Optical Filters

Lithium fluoride (LiF) and fused silica were used as filters to allow the VUV radiation to illuminate the surface, but not allow the energetic molecules or ions to reach the surface. Wavelengths longer than the filter cutoff wavelength are admitted into the sample. Table 2 shows the cutoff wavelengths and relative photon energies of the filters.
Table 1  Polymer structures and densities

<table>
<thead>
<tr>
<th>Polymer</th>
<th>STRUCTURE</th>
<th>DENSITY (g/cm³)</th>
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<tr>
<td>PTFE</td>
<td>(-{\text{CF}_2-\text{CF}_2}_n)</td>
<td>2.17 [48]</td>
</tr>
<tr>
<td>FEP</td>
<td>(-{\text{CF}_2-\text{CF}_2}_n{\text{CF}_2-\text{CF}_2}_n\text{CF}_3)</td>
<td>2.17 [48]</td>
</tr>
<tr>
<td>PI</td>
<td>(-\text{N}=\text{O}\left{\text{C}=\text{O}\right}_n\text{N}=\text{O}\left{\text{C}=\text{O}\right}_n\text{N}=\text{O}\left{\text{C}=\text{O}\right}_n)</td>
<td>1.42 [49]</td>
</tr>
<tr>
<td>UPILEX-S</td>
<td>(-\text{N}=\text{O}\left{\text{C}=\text{O}\right}_n\text{N}=\text{O}\left{\text{C}=\text{O}\right}_n\text{N}=\text{O}\left{\text{C}=\text{O}\right}_n)</td>
<td>1.47 [49]</td>
</tr>
<tr>
<td>UPILEX-R</td>
<td>(-\text{N}=\text{O}\left{\text{C}=\text{O}\right}_n\text{N}=\text{O}\left{\text{C}=\text{O}\right}_n\text{N}=\text{O}\left{\text{C}=\text{O}\right}_n)</td>
<td>1.39 [49]</td>
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Table 2

Optical filter with cutoff wavelength and corresponding photon energy

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<tr>
<th>Filter</th>
<th>Cutoff Wavelength (nm)</th>
<th>Corresponding Photon Energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiF</td>
<td>105 [50]</td>
<td>11.8</td>
</tr>
<tr>
<td>Fused Silica</td>
<td>160 [51]</td>
<td>7.8</td>
</tr>
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</table>

The filters were placed in the substrate holder against the polymer films as shown in Figure (4).

2.2.3 Exposure Temperature

The temperature of the substrate surface was monitored with a K type Ni/Cr - Ni/Al thermocouple (-200 to 1250 °C) placed in contact with the Al ring of the substrate holder.
Figure (4). Substrate holder
2.3 Analysis

2.3.1 Contact Angle

The contact angle between a drop of a liquid and the surface (Figure 5) is often used to determine the wettability of a surface and point its adhesion to another material [52]. The contact angle of a liquid drop on a solid surface is related to the various interfacial tensions by Young's Equation

\[ \cos \theta = \frac{r_s - r_{sl}}{r_l} \]

where \( r_l \) is the liquid surface energy, \( r_s \) the solid surface energy and \( r_{sl} \) the solid-liquid interfacial energy. From the equation, it can be seen that the contact angle will decrease when the solid surface energy increases, i.e. wettability increases.

All contact angle measurements were performed on an NRL C. A. Goniometer Model #100-00 115. The contact angle was the angle tangent of distilled water on the polymer film. When the angle was measured, the polymer films were mounted on titanium frames by compressing a titanium ring into the same frame (Figure 6). The advancing and receding contact angles, that are reported in this thesis, were determined from the average of 3-5 measurements of distilled water droplets on the right and left side. Advancing contact angles were the data of 10 µl of water added on the
Solid Figure (5). Contact angle
Figure (6). Titanium frames and ring used for holding sample during contact angle measurements.
polymer surface each time until 50 µl, i.e. 10, 20, 30, 40, 50 µl size drops. To obtain the receding contact angle, a 50 µl size drop of distilled water was placed on the polymer surface and then 10 µl water drops were removed. The receding contact angle at the final 10 µl drop size was called the “minimum” receding contact angle.

2.3.2 Weight Loss and Etch Rate

Weight loss measurements were performed on a microbalance (Mettler Instrument AG 1982, AE 163). Before weighing, all the polymer films were stored in a desiccator for more than ten minutes, then cleaned using a dust chaser (VWR Scientific Inc. : cat. no. TR 70230-50), and shot with a Discwasher Zerostat 3 Anti-Static Instrument. The etch rate (ER) in Å/min was calculated using the following equation.

\[ ER = \frac{\Delta m 10^8}{\rho A t} \text{ (Å/min.)} \]

where \( \Delta m \) is weight loss (g), \( 10^8 \text{Å} \) in one cm, \( \rho \) the density of the polymer film (g/cm\(^3\)) (Table 1), \( A \) the exposed surface area of the polymer film (3.88 cm\(^2\)), \( t \) the exposure time (min).
2.3.3 Sputtering

In order to study the adhesion between the modified polymer films and copper, a DC planar magnetron (US-Gun, Inc.) was used to sputter deposit copper onto the polymer surfaces. Figure (7) is a schematic representation of the sputtering chamber and the substrate holder. The polymer films were mounted on an aluminum plate substrate using Kapton stick tape. The aluminum plate clamped onto the substrate holder which was positioned directly in front of the copper target at a distance of 7.5 " from the copper target as shown in Figure (7). Typical sputter chamber conditions were: pressure = 5.26 or 2.16 mtorr, copper deposition rate 2.1 Å/s and Cu film thickness 2.5 kÅ.

2.3.4 Peel Test

A scotch tape peel test, as shown in Figure (8), was used to determine the adhesion between copper and polymer films. A piece of transparent tape was pressed onto the surface of the copper film and carefully peeled off by pulling at an angle of 90° with the film. A measure of the adhesion was determined by estimating the amount of copper which still remained on the polymer film after the peel test. The more copper remaining on the film, the better the adhesion.
Figure (7). Sputtering
Figure (8). Peel Test
2.3.5 Scanning Electron Microscopy (SEM)

SEM (ISI-40 International Scientific Instrument), as indicated in Figure (9), was used to view the polymer surface features. A 15 kV electron beam voltage was used in the experiment. The polymer films were placed on specimen stubs with double-coated adhesive tape, and then, the treated surfaces were coated with a thin (about 40 Å) layer of conducting material (Au/Pd) using an E 5000 SEM sputter coating unit (Polaron Instruments Inc.) before their examination with the microscope. The coating process was carried out with a 20 mA sputtering current and a 20 second sputtering exposure time. The tilt angle of incidence of the primary electron beam on the specimen surface was 45°, because the intensity of secondary electron emission is lowest when the specimen surface is normal to the beam. The SEM micrographs were taken at magnifications of about 4700 times.

2.3.6 Oven

Control experiments were done by placing polymer samples in an oven (VWR-1410, manufactured by Shel-Lab., Sheldon Manufacturing Inc.) under similar conditions as when the polymer was etched in rotating arc plasma, (500 torr He, temperature 160 °C or 240 °C). These experiments were carried out to determine if there was weight loss when the samples were treated in the absence of the arc.
Figure (9). Schematic Diagram of SEM
3.0 RESULTS

3.1 Exposure Temperature

Figure (10) is the temperature of aluminum ring surface next to the PTFE versus time when helium arc was used. Results will be reported for experiments done with exposure temperatures up to 110, 140, 160 and 240 °C.

3.2 PTFE

3.2.1 Weight Loss and Etch Rate

Figure (11) and (12) show the weight loss and etch rate versus exposure time for PTFE exposed to the helium arc without any optical filters at three different final temperatures (110 °C, 160 °C, 240 °C). Figure (13) and (14) are graph of the weight loss and etch rate, respectively, versus exposure time for PTFE that was exposed to helium arc with and without optical filters at the temperature up to 110 °C.

Figure (15) and (16) show the weight loss and etch rate plots, respectively, versus exposure time for PTFE which was exposed to an argon arc with and without filters at temperatures up to 110 °C. Figures
(17) and (18) are plots of weight loss and etch rate, respectively, versus exposure time for PTFE exposed to the argon arc with and without optical filters at temperatures up to 140 °C.
Figure (10). Substrate temperature versus exposure time for PTFE exposed to helium arc
Figure (11). Weight loss versus exposure time for PTFE exposed to helium arc without filter at different temperatures.

- □ -- 110°C,
- • --160°C,
- ■ --240°C
Figure (12). Etch rate versus exposure time for PTFE exposed to helium arc without filter at different temperatures.

- 110°C,
- 160°C,
- 240°C
Figure (13). Weight loss versus exposure time for PTFE exposed to helium arc with and without filters at temperature up to 110 °C

- no window,  ● --LiF,  □ --Fused Silica
Figure (14). Etch rate versus exposure time for PTFE exposed to helium arc with and without filters at temperature up to 110 °C

- □ --no window,
- ◆ --LiF,
- □ --Fused Silica
Figure (15). Weight loss versus exposure time for PTFE exposed to argon arc with and without filters at temperature up to 110 °C

- no window,
- LiF,
Figure (16). Etch rate versus exposure time for PTFE exposed to argon arc with and without filters at temperature up to 110°C

- no window,

--LiF
Figure (17). Weight loss versus exposure time for PTFE exposed to argon arc with and without filters at temperature up to 140 °C

- ■ --no window,
- ♦ --LiF,
- □ --Fused Silica
Figure (18). Etch rate versus exposure time for PTFE exposed to argon arc with and without filters at temperature up to 140 °C

- no window,  - LiF,  - Fused Silica
3.2.2 Contact Angle

The receding contact angle of PTFE was measured for both untreated and treated samples. Table 3 and Figure (19) shows the "minimum" receding contact angle for PTFE versus exposure time to VUV radiation from a He arc without filters at different exposure temperatures, 110 °C, 160 °C, 240 °C. Figure (20, 21) show the "minimum" receding contact angle versus the cutoff wavelengths for PTFE exposed to helium and argon arc at temperatures up to 110 °C. The contact angles of treated samples that were reported in Figure (20) and (21) were measured after 60 minutes treatment.
Table 3

"Minimum" receding contact angle versus exposure time for PTFE exposed to helium arc without filters at different exposure temperature

initial receding contact angle = 101°

<table>
<thead>
<tr>
<th>°C</th>
<th>min</th>
<th>1</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>120</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>61</td>
<td>47</td>
<td>41</td>
<td>34</td>
<td>34</td>
<td>41</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>47</td>
<td>49</td>
<td>52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>240</td>
<td>46</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>

Chamber pressure = 500 Torr, Arc current = 7 A, Magnetic current = 3 A,
Gas flow rate = 0.082 l/s, Distance from Substrate to Arc = 5 cm,
Rotational frequency of the arc = 130 Hz, Magnetic field strength = 94 gauss.
Figure (19). "Minimum" receding contact angle versus exposure time for PTFE exposed to helium arc without filters at different temperatures

- □ -- 110 °C,
- ■ -- 160 °C,
- ● -- 240 °C
Figure (20). “Minimum” receding contact angle versus cutoff wavelength for PTFE exposed to helium arc at exposure temperature up to 110 °C
Figure (21). "Minimum" receding contact angle versus cutoff wavelength for PTFE exposed to argon arc at exposure temperature up to 110 °C.
3.3 UPILEX-S

3.3.1 Weight Loss and Etch Rate

Figure (22) and Table 4 show the weight loss versus exposure time for UPILEX-S exposed to the helium arc with and without filters at exposure temperature up to 110 °C.

3.3.2 Contact Angle

The advancing and receding contact angles for UPILEX-S were measured for both untreated and treated samples with or without filters. Table 5 and Figure (23) show the advancing and receding contact versus exposure time for UPILEX-S exposed to the helium arc without filters. Figure (24) is the graph of "minimum" receding contact angle versus cut off wavelength for UPILEX-S that were exposed to helium arc for one hour.
Table 4

Weight loss and etch rate for UPILEX-S, and -R exposed to helium arc with and without filters

<table>
<thead>
<tr>
<th></th>
<th>Weight Loss (g) at Different Exposure Time</th>
<th>Etch Rate (Å/min) at Different Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 h</td>
<td>2 h</td>
</tr>
<tr>
<td>UPILEX-S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>no window</td>
<td>0.00038</td>
<td>0.00038</td>
</tr>
<tr>
<td>LiF</td>
<td>0.00006</td>
<td>0.00006</td>
</tr>
<tr>
<td>UPILEX-R</td>
<td></td>
<td></td>
</tr>
<tr>
<td>no window</td>
<td>0.00032</td>
<td>0.00032</td>
</tr>
<tr>
<td>LiF</td>
<td>0.00020</td>
<td></td>
</tr>
</tbody>
</table>

Chamber pressure = 500 Torr, Arc current = 7 A, Magnetic current = 3 A, Gas flow rate = 0.082 l/s, Distance from Substrate to Arc = 5 cm, Rotational frequency of the arc = 130 Hz, Magnetic field strength = 94 gauss.
Figure (22). Weight loss versus exposure time for UPILEX-S exposed to helium arc with and without filters at temperature up to 110 °C

♦ — no window, □ — LiF,
**Table 5**

Advancing and receding contact angle for UPILEX-S and -R exposed to He arc without filters at temperatures up to 110 °C

<table>
<thead>
<tr>
<th></th>
<th>Initial Contact Angle (degree)</th>
<th>Contact Angle (degree) After 1 Hour Exposure</th>
<th>Change in Contact Angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>receding</td>
<td>advancing</td>
<td>receding</td>
</tr>
<tr>
<td>UPILEX-S</td>
<td>55</td>
<td>73</td>
<td>6</td>
</tr>
<tr>
<td>UPILEX-R</td>
<td>69</td>
<td>78</td>
<td>12</td>
</tr>
</tbody>
</table>
Figure (23). Advancing and Receding contact angle versus exposure time for UPILEX-S exposed to helium arc without filters at temperature up to 110 °C

- Advancing contact angle
- Receding contact angle
Figure (24). First hour "minimum" receding contact angle versus cutoff wavelength for UPILEX-S exposed to helium arc at exposure temperature up to 110 °C
3.4 UPILEX-R

3.4.1 Weight Loss and Etch Rate

Figures (25) and Table 4 show the weight loss versus time of UPILEX-R samples exposed to the helium arc with and without filters.

3.4.2 Contact Angle

The advancing and receding contact angles of UPILEX-R were measured for both untreated and treated samples with and without filters. Table 5 and Figure (26) show the advancing and receding contact versus time for UPILEX-R samples that were exposed to the helium arc without filters. Figure (27) is the graph of “minimum” receding contact angle versus cutoff wavelength for UPILEX-R exposed to the helium arc for one hour.
Figure (25). Weight loss versus exposure time for UPLEX-R exposed to helium arc with and without filters at temperature up to 110 °C

- ◇ -- no window,  □ -- LiF,
Figure (26). Advancing and Receding contact angle versus exposure time for UPILEX-R exposed to helium arc without filters at temperature up to 110 °C

- Advancing contact angle
- Receding contact angle
Figure (27). First hour "minimum" receding contact angle versus cutoff wavelength for UPILEX-R exposed to helium arc at exposure temperature up to 110 °C.
3.5 Polyimide

3.5.1 Contact Angle

Figure (28) shows the "minimum" receding contact angle versus cutoff wavelength for polyimide exposed to the helium arc at the maximum temperature of 110 °C for one hour.
Figure (28). "Minimum" receding contact angle versus cutoff wavelength for polyimide exposed to the helium arc at exposure temperature up to 110 °C for one hour.
3.6 Sputtering and Peel Test

Copper was sputtered deposited on some selected samples, then the adhesion between copper and polymer films were measured by using peel test. Table 6 shows the samples, conditions of sputtering and the results of the peel test.

3.7 Oven

PTFE were exposed to helium in an oven at a pressure of 500 torr, and exposure temperature as high as 160 °C and 240 °C. No weight loss was observed after being in the oven for one hour.
Table 6

Adhesion Studies of VUV Modified Polymers Deposited With Copper\textsuperscript{a, b}

<table>
<thead>
<tr>
<th>Material</th>
<th>Filter</th>
<th>Exposure Time(min)</th>
<th>Radiation Source</th>
<th>Sputter Chamber Pressure(mtorr)</th>
<th>Copper Deposition Rate(Å/s)</th>
<th>Copper Film Thickness kÅ</th>
<th>Adhesion</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEP</td>
<td>None</td>
<td>60</td>
<td>He</td>
<td>5.26</td>
<td>2.1</td>
<td>2.5</td>
<td>Poor</td>
</tr>
<tr>
<td>LiF</td>
<td>60</td>
<td>He</td>
<td>5.26</td>
<td>2.1</td>
<td>2.5</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>PTFE</td>
<td>None</td>
<td>60</td>
<td>He</td>
<td>2.16</td>
<td>2</td>
<td>2.766</td>
<td>Poor</td>
</tr>
<tr>
<td>LiF</td>
<td>60</td>
<td>Ar</td>
<td>5.26</td>
<td>2.1</td>
<td>2.5</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>Fused Silica</td>
<td>60</td>
<td>He</td>
<td>5.26</td>
<td>2.1</td>
<td>2.5</td>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>Polymide</td>
<td>Fused Silica</td>
<td>60</td>
<td>Ar</td>
<td>2.16</td>
<td>2</td>
<td>2.766</td>
<td>100%</td>
</tr>
<tr>
<td>UPILEX-S</td>
<td>Fused Silica</td>
<td>60</td>
<td>Ar</td>
<td>2.16</td>
<td>2</td>
<td>2.766</td>
<td>100%</td>
</tr>
</tbody>
</table>

\textbf{a. Rotating arc experiment:}

Chamber pressure = 500 Torr, Arc current = 7 A, Magnetic current = 3 A,
Exposure temperature = 110 °C, Gas flow rate = 0.082 l/s, Distance from Substrate
to Arc = 5 cm, Rotational frequency of the arc = 130 Hz

\textbf{b. Distance from target to sample during copper deposition = 7.5 in.}
3.8 SEM

Figures (29), (30) and (31) show micrographs of the surface roughness of PTFE: before treatment, one hour after treatment in a helium arc with LiF filter and two hours after treatment in a helium arc without filters. The exposure temperature went up to 110 °C. Figures (32) and (33) are the micrographs of surface roughness for untreated and treated UPILEX-R in a helium arc for two hours without filter at the exposure temperature up to 110 °C and magnified around 4900 times. The untreated samples show smooth surfaces. After two hours treatment in helium without UV filter, UPILEX-R shows a slightly rougher surface than compared to the untreated sample. For PTFE, the samples treated without the filter shows the largest degree of surface roughness.
Figure (29). SEM micrograph of untreated PTFE
magnified 5.7 KX, tilt 30°
Figure (30). SEM micrograph of PTFE exposed to helium arc with LiF filter at temperature up to 110 °C for one hour

magnified 5.6 KX, tilt 30°
Figure (31). SEM micrograph of PTFE exposed to helium arc without filter at exposure temperature up to 110°C for two hours magnified 4.8 KX, tilt 30°
Figure (32). SEM micrograph of untreated UPILEX-R

magnified 5.5 KX, tilt 30°
Figure (33). SEM micrograph of UPILEX-R exposed to helium arc without filter at exposure temperature up to 110 °C for two hours.

magnified 4.7 KX, tilt 30°
3.9 Standard Deviation

In order to place an error limit on the weight loss and contact angle measurements, a sample was measured 11 times on the microbalance and 14 times on the goniometer. The standard deviation was calculated using the equation shown below:

\[ \sigma = \sqrt{\frac{\sum (x-\mu)^2}{N}} \]

\( X \) is the actual measured data, \( \mu \) the mean of the measured data, and \( N \) the number of measurement. The standard deviation for the weight loss and contact angle measurements were found to be \( \pm 0.000013 \) g and \( \pm 3 \) degree respectively.
4.0 DISCUSSION

4.1 PTFE

4.1.1 Weight Loss and Etch Rate

Figures (11-18), show that no matter what radiation source, exposure temperature and filters were used, the weight loss for PTFE increased proportionally with time and the etch rate went up to a constant value. Figures (11, 15, 17) show that the weight loss for PTFE increases with exposure temperature. But, when PTFE was exposed to helium in an oven under the same exposure temperature and chamber pressure as in experiments with rotating arc, there is no weight loss at all. On the other hand, there is a difference when helium and argon are used as the VUV radiation sources. When the polymer film was exposed to helium arc, the exposure temperature affected the etch rate very much. However, when this polymer film was exposed to argon arc, the exposure temperature affected the weight loss slightly. The radiation source, that was used in the experiments reported here, was designed to minimize the interaction of He and Ar ions and metastables with the organic polymer substrate and to maximize the effects of the radiation on the polymer. When the optical filters were in place, ions and metastables were prevented by the filters from interacting with the substrate and only photons with wavelengths longer than the cutoff wavelength were responsible for the modification of
the polymer surface. Even in the absence of filters, at the near atmospheric pressure of the source substantial deactivation and recombination processes involving ions and metastables would make their concentrations negligible at the substrate and hence minimize their influence on the polymer surface. At the low arc current 7A used in these experiments, a two-temperature model of an Ar arc plasma shows that the temperature of the electrons and heavy particles (atoms and ions) in the plasma decrease with radial distance from the center of the arc where T 10,000 K [54]. The model clearly indicates (e.g., Figures. 8.3 and 8.5 of ref. [54]) that the temperatures of the electrons and heavy particles are nearly equal and are not substantially different from room temperature at the distance 5 cm that the substrates were placed from the arc in this thesis. Changing the inert gas from Ar to He should affect the wavelength distribution of the emission spectrum. HeI, HeII and Hez* emission occurs at shorter wavelengths than the corresponding ArI, ArII and Arz* emission [46]. For similar experiments, the photoetch rate is larger using the more energetic photons produced from He than from Ar. Figures (14, 16, 18) show that the etch rate will decrease when the filters cutoff wavelength limit is increased to higher wavelength and smaller energies. For wavelength below 105 nm, photon energies higher than 11.8 eV, the etch rate is the highest. This may be due to a greater number of photons reaching the surface than in the case when windows are present, although the effect may still probably be described to the photon energies.
4.1.2 Contact Angle

Figure (19) and Table 3 show the receding contact angle vs. time for PTFE exposed to He arc without filters. The receding contact angle initially decreases rapidly with exposure time and then approaches a constant value. This figure is quite similar with that obtained by F. D. Egitto et al. who treated PTFE downstream from a helium microwave plasma [13]. Receding contact angles showed little dependence on exposure temperatures. Figures (20 and 21) show that with arcs containing helium and argon, the “minimum” receding contact angle of PTFE increases as the cutoff wavelength limits of the filters increase to high wavelength.

4.2 UPILEX-S and -R

4.2.1 Weight Loss and Etch Rate

UPILEX-S and -R showed an initial weight loss and then negligible weight loss with increasing time of exposure to the He arc (Figure 22 and 25). The initial weight loss decreased as the cutoff wavelength of the filter increased allowing less energetic photons to reach the substrate (Table 4). Photochemical modification of UPILEX-S and -R is expected to result in loss of unsaturation, like polybutadiene and polyisoprene polymers [42-45], with possibly an increase in the rate of crosslinking relative to
photoetching, in contrast to PTFE which undergoes defluorination [13] and more rapid rupture of the polymer backbone compared to crosslinking.

4.2.2 Contact Angle

Figure (23, 26) and Table 5 show that the advancing and receding contact angle decrease during the first hour of exposure and then at longer times shows almost no change when UPILEX-S and -R were exposed to helium arc. From Figures (24 and 27), it can be seen that the receding contact angle increases when the cutoff limit increases to higher wavelengths.

4.3 Kapton (Polyimide)

From Figure (28), it can be seen that as the cutoff limit increases to high wavelength, there is no big change in the “minimum” receding contact angle. Indicating that $\lambda \geq 160$ nm are most effective in causing the modification.
4.4 Sputtering and Peel Test

Selected samples of PTFE, FEP, Polyimide and UPILEX-S, which were exposed to vacuum UV radiation from a helium and argon arc for one hour, were deposited with copper using the electron assisted copper deposition system. PTFE and FEP showed poor adhesive properties. PI and UPILEX-S showed good adhesion with copper after modification.
PTFE exposed to VUV radiation showed weight loss proportional to exposure time and etch rate increasing to a constant value when the exposure time was increased. Weight loss for UPILEX-S, and -R are increased up to a constant value when the exposure time is increased, and the each rate goes to zero with increasing time. For PTFE, the weight loss were increased when the arc current [55], exposure temperature and photon energies were increased. The receding contact angle of the polymer surfaces studied decreases as photon energy increased in the rotating arc experiment. With increasing exposure time, the receding contact angle decreases down to a constant value which has been shown to be independent of exposure temperature. The roughness of polymer surfaces, PTFE and UPILEX-R have been shown to increase proportionally with photon energy in the rotating arc experiment. Polyimide and UPILEX-S show good adhesion with copper after exposure to an argon arc with fused silica filter. Future work on this project may include exposure of polymers to VUV radiation using different thickness of filters to change the photons number attaching the polymer surface. To stabilize the temperature at the surface of the polymer, a temperature regulating system could also be developed.
REFERENCES


24. du pont Bulletin H-1A.


