

Improved Biocompatibility of Parylene-C Films Prepared by Chemical Vapor Deposition and the Subsequent Plasma Treatment

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Received 8 February 2007; accepted 23 September 2008

DOI 10.1002/app.29774

Published online 12 March 2009 in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: The purpose of this study is to prepare the thin film of C-type parylene (C-type polyxylylene, parylene-C) with improved biocompatibility for the biomedical applications, since in spite of the popularity, the parylene-C has been known to have the less biocompatibility than the N-type or D-type parylene. To prepare the well-designed parylene films through the chemical vapor deposition (CVD) process and the subsequent plasma surface treatment, the parameters of deposition and surface modification were controlled to obtain optimized physical and surface properties. Using CVD, the thin films of parylene-C as thick as 5 μm were prepared under different deposition pressures. When increasing the deposition rate of parylene film or the deposition pressure, the tensile strength

of film increased, whereas the properties such as the surface contact angle and permeability, and the elongation decreased. The deposition rate could be controlled to optimize the physical and physiochemical properties of films. The hydrophilicity of the parylene-C film increased after plasma surface treatment by showing the larger water contact angle than untreated one. When the radio frequency power was above 100 W in the plasma process, the thin film obtained reveals an excellent cytotropism. It shows the improved biocompatibility with living cells. © 2009 Wiley Periodicals, Inc. *J Appl Polym Sci* 112: 3677–3685, 2009

Key words: biocompatibility; plasma; surface modification; hydrophilicity; cytotoxicity

INTRODUCTION

The parylenes as medical polymers classified in USP Class VI are known to show good biocompatibility and chemical resistance. The parylene is a generic name of unique polymer series, and there are several kind of parylenes based on monomer derivatives. The parylene-N (poly-*p*-xylylene) is a linear and highly crystalline polymer. The parylene-C has one chlorine molecule substituted on the aromatic ring and the parylene-D has two Cl substituted. The parylene-F with fluorine substituted on the aromatic ring shows high temperature stability in air. The thin films of parylenes can be used as a dense and nonpermissive film for protecting the substratum due to no pin-hole on surface.^{1–10}

The parylene-N and parylene-C are used widely as coating materials in industrial and medical applications. The parylene-N is a dielectric material, exhibiting very low dissipation factor, high dielectric strength, and a dielectric constant invariant with frequency, but it shows too weak strength to be used for specific coating applications. The parylene-C has

the balanced combination between electrical and physical properties, and very low permeability to moisture or other corrosive gases. In our previous study, the parylene-C was found to show less cell biocompatibility than the parylene-N or parylene-D.¹¹ Its less biocompatibility can be presumably attributed to the asymmetric characteristic of the chlorine molecule acting a significant role in disinfection. For medical applications, it should thus submit to a delicate postprocess, although we anticipate the loss of biocompatibility to some extent from such process.

Many techniques can be used for modifying the surface characteristics and improving biocompatibility of materials.^{12–19} Among them, the ion beam assistive deposition and plasma surface treatment have been interested by many researchers, and the plasma treatment can be used popularly for modifying surfaces of the materials such as metal, plastics, ceramics, and glasses, etc. When plasma is exposed on the surface in its ionized gas state, various chemical and physical modifications of surface can occur.^{20–23} Depending on the condition of the plasma treatment and its environments, the surface activation/passivation, functionalization, implantation, the chemical dissociation, and crosslinking of surface molecules, and/or etching can be involved on the surface of polymer. These basically lead to the modification of the physical/chemical structure of surface

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Contract grant sponsor: Ministry of Health and Welfare, Korea; contract grant number: 02-PJ3-PG10-31402-0001.

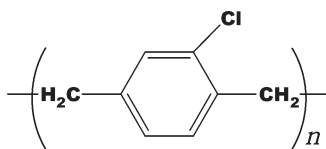
molecules and/or the creation of the new specific functional groups which may increase either hydrophilicity or hydrophobicity of surfaces. Ionization of gas to generate plasma can be conducted in wide ranges of wave frequency from low frequency (<100 kHz), and radio frequency (RF) (13.56 MHz), to microwave frequency (MW) (2.45 GHz), and the RF plasma is popularly used because it can generate the plasma of high concentration of ionic particles and homogeneous state.

The good surface properties of materials are required particularly for medical applications. In this study, we intended to improve the biocompatibility of the thin film of parylene-C as a surface coating material, which could be obtained from the combined process of chemical deposition on substrate and the plasma surface treatment. We prepared thin films of parylene-C on both stainless steel and glass substrates with a chemical vapor deposition (CVD) device particularly designed for parylene coating. The physical properties of the films depending on the deposition rate were investigated. We also observed the effect of the physical roughness of substrate on the electric insulation of parylene, in each case that the surface of stainless steel used as substrate was sandblasted or microblasted. Second, the parylene film was deliberately treated with the plasma of different RF powers. Its surface morphology and biocompatibility were analyzed and other characteristics were evaluated from FTIR, XPS, and SEM.

EXPERIMENTAL

Materials

The parylene used in this study is a powder type of C-type dimer (parylene-C) (Specialty Coating Systems, Indianapolis, IN), and its chemical structure is shown as following:



The coating substrate was stainless steel (SUS304) sheet. The sandblasting using 90 mesh was carried out on the surface of stainless steel under the pressure of 4 kg/cm³. And microblasting of the stainless steel surface with 30 μm particles was performed at 2.0 bar using Microblasting equipment (PEEN-MATIC 750S, IEPCO AG, Swiss). All stainless steel specimens were dried for 1 h at 70°C after cleaning twice with isopropyl alcohol before deposition.

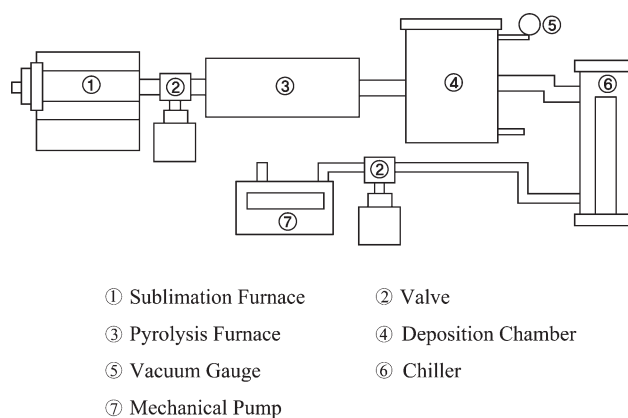


Figure 1 Schematic diagram of the experimental setup used for parylene-C deposition.

Deposition of parylene and plasma treatment for surface modification

The parylene-C was deposited on the stainless steel using a Chemical Deposition System for Parylene (PDS-2060PC, SCS) with a thickness of 5 μm film, and its scheme was shown in Figure 1. The pressure of deposition chamber was varied to obtain the correlation between a deposition rate and the properties of deposited films. Before deposition, the target films underwent ultrasonic cleaning and washing with alcohol and distilled water. The films were mounted in the chamber, and the deposition was initiated by heating the dimers at the time when the vacuum pressure in the chamber reached ~ 18 mTorr. The deposition rate of parylene could be controlled by regulating the evaporation of dimers in the chamber from controlling the chamber temperature. The increased chamber temperature leads to both the higher deposition rate and vapor pressure of parylene dimers. The test specimens for measuring the physical property were obtained by being removed from the glass substrates on which parylene was deposited with releasing agent.

The plasma treatment was conducted on the surface of parylene to acquire the improved hydrophilicity and biocompatibility of thin films. The parylene film underwent the ultrasonic cleaning with isopropyl alcohol beforehand for plasma treatment. The plasma treatment system (WRD-1000, GV Tech, Korea) equipped with power system (OEM-6, ENI) was used in this study. The RF power chosen was 50, 100, and 150 W, and the Ar, O₂ gas and the Ar + O₂ (50 : 50) gas mixture were used for flushing for 60 s. The base pressure indicating the vacuum pressure of minimum at which the chamber reaches before the gas injection was 5 × 10⁻⁶ Torr, and the working pressure for treatment was 10 mTorr, which could be controlled by regulating influx of the gases for plasma.

Thin film analysis

To measure tensile properties of parylene films, the thin layer detached from the glass was fabricated into the standard specimen of dumbbell type (KS M 6782 dumbbell #2). The universal test machine (Tinius Olsen Ltd, H10KS, UK) was used, and the cross head speed was 0.2 mm/s.

Wetting properties before and after plasma treatments were measured with the Contact Angle Meter (G-1, ERMA Inc., Japan). The drop of distilled water with a diameter of 1.5–3 mm was fallen on the surface, and the value of the contact angle was averaged from three measurements. The surface roughness and morphology of substrate and deposited parylene film were investigated with the Surface profilometer (P-10, Tencor, Santa Clara, CA) and the Atomic Force Microscope (AFM, NanoScope III, Digital Instruments, Veeco Metrology Group, Santa Barbara, CA), respectively. The deposition rate of parylene and its film characteristics were analyzed through the infrared spectroscopy (FTIR, EQUINOX 55, Bruker, Germany) and UV-Visible spectroscopy (VARIN, Inc., CARY 300Bio, Australia).

With parylene coating on the stainless steel substrates with different initial roughness from pretreatment, the breakdown voltage of the deposited film was measured through ASTM D 149 test method using the breakdown voltage tester (HB9901, PUNCTURE TEST, NARA System, Korea). The breakdown voltage was decided and recorded when the limit of current set as 0.5 A was reached at the preset voltage with the increment of voltage by 200 V after maintaining the specimen for 5 s at initial voltage.

The chemical shifts of bonds due to the plasma treatment were analyzed with X-ray Photoelectron Spectroscopy (XPS, ESCA2000, VG Microtech, UK). The base pressure was set to 1.0×10^{-9} mbar. The Al Ka was used as X-ray source, and its power was 170 W. The EDX system (Oxford Instruments, Bucks, UK) equipped with Scanning Electron Microscope (SEM, JSM-5310, JEOL, Tokyo, Japan) was used to determine the composition of C and Cl of the deposited film.

For the biocompatibility test, the human osteosarcoma (HOS) cell was cultured in dish containing Dulbecco's modified Eagle's medium (DMEM, Life Technologies, Inc.) supplemented with 10% fetal bovine serum (Life Technologies, Inc.) at $37 \pm 1^\circ\text{C}$ for 24 h. To measure the effect of each material on the growth of the cells, the fabricated specimens of Thermanox cover slip as a control were placed in individual wells of 24-well plate, and 1.5×10^3 cells/cm² were plated onto the discs. Cells were cultured for 4 days in incubator humidified with 5% CO₂ at 37°C after dipping the specimen in DMEM and the number of the remaining cell was counted. The opti-

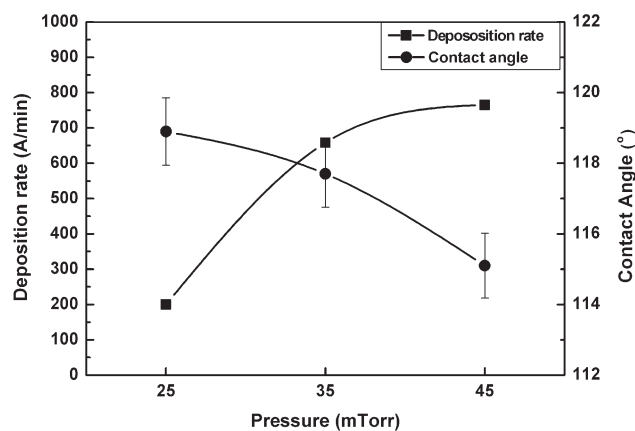


Figure 2 Deposition rate and contact angle versus reactor pressure for parylene-C films at room temperature.

cal density of cell was measured with a spectrophotometer using optical wavelength of 490 nm. As the number of cells increase the culture fluid gets thick. OD measured at 490 nm presents the density of cell. Results can be expressed as the mean optical density with $\pm 95\%$ confidence limits.

RESULTS AND DISCUSSION

Effect of the deposition pressure in the deposition process

Figure 2 shows changes of the deposition rate and the surface contact angle according to the deposition pressure in chamber. As the chamber pressure increases, so does the deposition rate of which the slope gets lower at higher pressure, while the contact angle decreases. The factors governing the deposition rate are gas flow rate, substrate temperature, reactant partial pressures, crystallographic substrate orientation, geometrical substrate orientation, and substrate surface area, etc. As one of the important parameters, the pressure of monomer in the chamber is directly correlated with the CVD reaction rate and subsequently deposition rate.²⁴

The interfacial concentration (M_{fi}) of monomer in the deposited film can be estimated using Flory's equation as following:²⁵

$$M_{fi} \propto \frac{P}{P_{sat}} \quad (1)$$

where P is the partial pressure of monomer and P_{sat} is the vapor pressure of pure monomer at the substrate temperature. Equation (1) indicates that the interfacial concentration (M_{fi}) of monomer is proportional to the partial pressure of monomer. Correspondingly, the higher pressure of chamber leads to the higher interfacial concentration of monomer, and thus it induces the higher deposition rate.

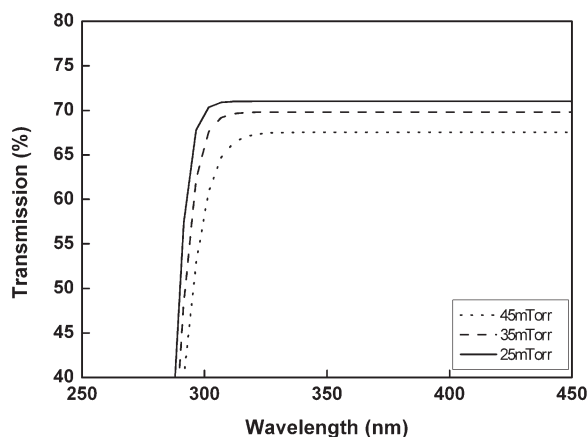


Figure 3 Transmission curves of parylene-C films prepared at different deposition pressures.

The gradual reduction of contact angle when the pressure increases indicates that the surface free energy increases due to the existence of relatively more polar components at surface.²⁶ Thus, the surface with the lower contact angle prepared at the higher pressure has relatively the higher surface tension and hydrophilicity, and then the better wettability.

The change of transmittance of thin film according to the deposition pressure is shown in Figure 3. When the pressure is changed as 25, 35, and 45 mTorr, the transmittance is 71, 70, and 68%, respectively. With the increasing pressure, the transmittance lowers. The thin film deposited at high chamber pressure had rough surface of milky-colored globules structure, which reflects the microscopic nature of the polymerized chains forming on the surface.²⁴ The polymerization of parylene is the free radical reaction composed of initiation, propagation, and termination step. The high deposition pressure increases the inflow of dimer into the deposition chamber. The dimers in the phase of vapor are decomposed to form monomers, and they are condensed on the surface of the substrate. At the initiation step, two monomers existing near on the surface react to form double radical intermediates. Both the ends of double radicals are propagated with adding monomers, and thin films of parylene grow. At the termination, the ends of intermediate chain radicals are hindered in the bulk of parylene film, where monomers are not accessible to living radicals any longer. The adhesion of monomer on the substrate is known as the rate determining step, while the monomer addition to intermediate chains is considered to occur quickly. If the deposition rate is too high, the reaction time of the ends of double radicals to polymerize gets reduced. Therefore, the average molecule weight of the film becomes low

and the film turns milky-colored and of coarse nature of surface.

Figure 4 shows the physical properties of parylene films prepared at different chamber pressures. With the samples prepared at the higher chamber pressure, the strength at break was smaller and the elongation was higher. These behaviors are definitely due to both the crosslink density and molecular weight of the films formed. The change of the strength at break appears to be relatively less sensitive to deposition rate, being smaller in percent range than the change of elongation, when considering that the first diminishes only by $\sim 20\%$ from 2.7 N at 25 mTorr to 2.3 N at 45 mTorr, whereas the latter increases about five times from 22.2% at 25 mTorr to 119% at 40 mTorr.

To measure the breakdown voltage of thin films deposited on the stainless steel substrate with different surface roughness, we had made three substrates with different surface roughness, which was prepared by no blasting ($R_a = 0.1 \mu\text{m}$), sandblasting ($R_a = 1.5 \mu\text{m}$), or microblasting ($R_a = 0.5 \mu\text{m}$). The film by microblasting shows the similar break voltage (ca. 1480 V) with nonblasted smooth substrate (ca. 1420 V). In case of sandblasting offering higher roughness, the breakdown voltage of the film was quite as low as 430 V, although the adhesion between film and substrate was improved. It was very interesting to see that the good adhesion does not necessarily lead to the increase of the breakdown voltage. In other words, the optimal range of surface roughness should be investigated to satisfy both the required breakdown voltage and tolerable adhesion. The breakdown voltage indicates the electric voltage at which physiochemical rupture of the film by electric damage begins to occur under the voltage applied. It is important in the meaning that we need to set up and control the limit of applied voltage in

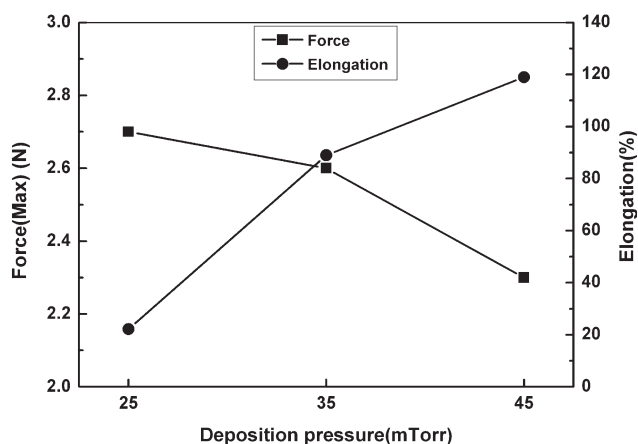


Figure 4 Plots of maximum force and elongation of parylene-C films as a function of deposition pressure.

applications of the parylene such as the surface coating of medical needles used for electric stimulation or therapy. In those applications, its high breakdown voltage leading to the good electric insulation of the coating is required significantly to prevent the probable electric damage on the living skins occurring around the target where the needle may be injected for electric stimulation.

Effect of plasma treatment on the thin film of parylenes

Plasma treatment as a nondestructive process was usually conducted at high vacuum pressure. Such vacuum operation required great expenses and thus the technique has been less popular. Since Okazaki and coworkers^{27,28} recently developed the plasma treatment at ambient pressure, it began to be used for modifying surfaces of polymer materials and the materials with high vapor pressure. In our previous study, we have found that the parylene-C has lower cytotoxicity than other parylenes through cytotoxicity test using different parylenes.¹¹ This subsequent study was intended to improve the cytotoxicity of parylene-C through the plasma treatment on the surface of thin film.

Figure 5 shows the surface morphology of the parylene film as deposited (without plasma treatment) and the surface treated with oxygen plasma at RF power 150 W for 60 s. There is little significant difference in overall surface roughness between surfaces with plasma treatment ($R_a = 119 \text{ \AA}$) and without it ($R_a = 110 \text{ \AA}$). On the other hand, the local microscopic shape of roughness topology of the plasma treated surface appears smoother in figures. There are several major factors influencing the modification of the surface morphology, that is, the surface passivation/activation, functionalization, modification, implantation, chemical etching, and so on.

Basically speaking, collisions of the plasma species with the polymer surface can result in one of three types, depending on the kinetic energy of the plasma species and the frequency of collisions.²³ If the kinetic energy of the charged plasma species is too low, a collision between the plasma species and the surface will fail to initiate a reaction. If the kinetic energy is too high, the collisions between the plasma species and the polymer surface will lead to the scission of the polymer chain and the formation of radicals at the polymer-chain ends. Radicals formed through chain scission can undergo crosslinking reactions. However, if the process of chain scission is very rapid and the rate of chain terminating radical formation is faster than that of crosslinking reactions, etching of the polymer surface will be observed. The etching can be also considered in the way that the momentum transfer of ion bombard-

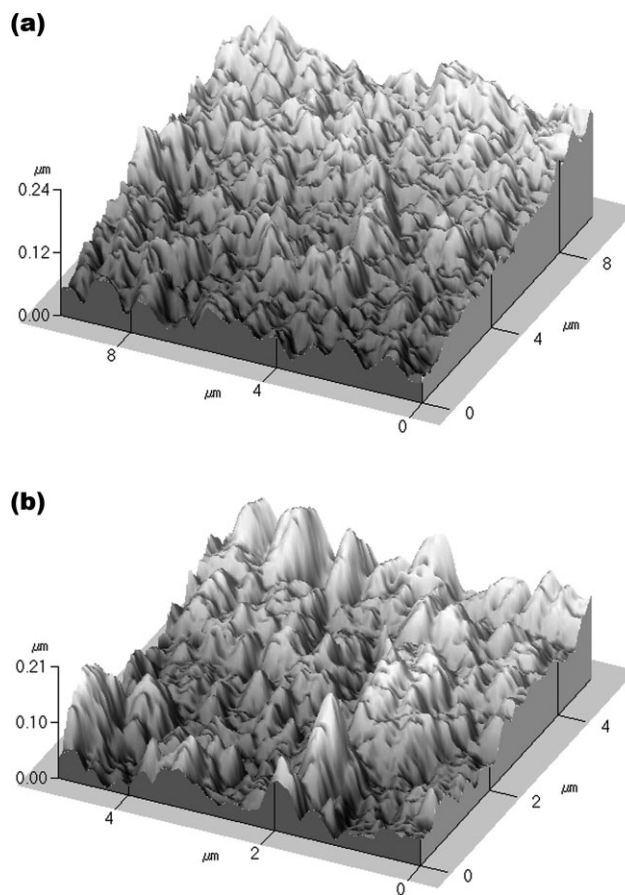


Figure 5 AFM and 3-dimensions profiler images of surface morphology for parylene-C films with (a) no treatment and (b) oxygen plasma treatment at 150 W for 60 s.

ment causes sputtering of atoms and/or molecules on the polymer surface as well as free radical formation, bond scission, and chemical reactions.

With certain amount of kinetic energy of polymer surfaces, the collisions can initiate ion-implantation reactions responsible for the chemical modification of polymer surfaces. Without chain scission through the displacement of directly from the polymer chain, radicals of this type, formed within the polymer chain itself, can either react with nearby chains to form crosslinks, undergo a rearrangement that results in chain scission, or recombine with reactive species in the plasma, such as ions and free radicals, to generate chemical functionalities. With combined effects by plasma treatment, the chemical state of polymer surface rather than the physical appearance such as roughness of surface was thought to become changed more considerably, as shown as the AFM result of Figure 5.

The surface contact angles were measured at the different RF powers in various gases during the plasma treatment. The contact angle of untreated film was 117° , which belongs to the range of relatively high hydrophobicity as expected, while

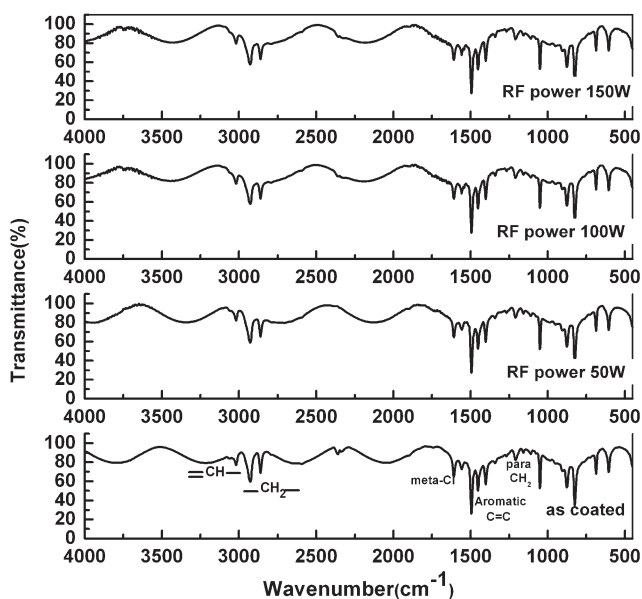


Figure 6 FTIR transmission spectra of the parylene-C films prepared at different RF powers.

modified surfaces showed highly improved hydrophilicity with smaller contact angle. For Ar, Ar/O₂, and O₂ used as gases, the contact angles were 50, 41, and 26.3°, respectively, when the RF power was 50 W. The oxygen plasma was the most effective in lowering the contact angle among the gases explored. Changes of wetting angle with oxygen gas and Ar⁺ ion irradiation could be explained by a two-step chemical reaction among polymer matrix, energetic ions, and oxygen gas. The effects of Ar⁺ ion and oxygen ion irradiation were explained by considering formation of hydrophilic groups due to a reaction between irradiated polymer chain by energetic ion irradiation and blown oxygen gas. Thus, oxygen as reactive gas mainly causes chemical reactions and thus induces etching effects, whereas Ar⁺ influences in surface cleaning and remnant radical effect. With change of contact angle, the Ar⁺ without the reactive gas rather reduces the contact angle due to those effects. With increase of oxygen, the polar functional groups increase the surface energy and wettability leading to the increase of contact angle.²⁹

When the RF power was set to 100 and 150 W, the noticeable difference of contact angle (around 40°) was detected among plasmas from different gases used for treatment. The reduction in the contact angle is attributed to hydrophilic functional groups forming near the surface, mainly around which imposed plasma activated many kind of chemical reactions. The oxygen plasma initiates intermolecular reactions to make different functional groups such as C=O, C-O, O-C=O, C-O-O, and CO₃, etc. The formation of those polar groups leads to increase effectively surface energy and hydrophilicity particularly at surface.

The FTIR spectra of the surfaces subjected to plasma treatment with different RF powers are shown in Figure 6. The peak around 1500 cm⁻¹ is assigned to C=C in-plane vibration or -CH₂-, and the peaks of *meta*-Cl and *para*-Cl can be detected near the peak. The peaks of 800 and 3000 cm⁻¹ are attributed to out-of-plane C-H wagging and C-H stretching, respectively. It can be shown that the peak of aromatic ring (C=C) increases as the progress of deposition, during which the monomers are polymerized to form a polymeric chain along the polymer/metal interface, and the polymer is subsequently deposited on the surface.³⁰ By the way, there was found no significant change of IR peaks due to

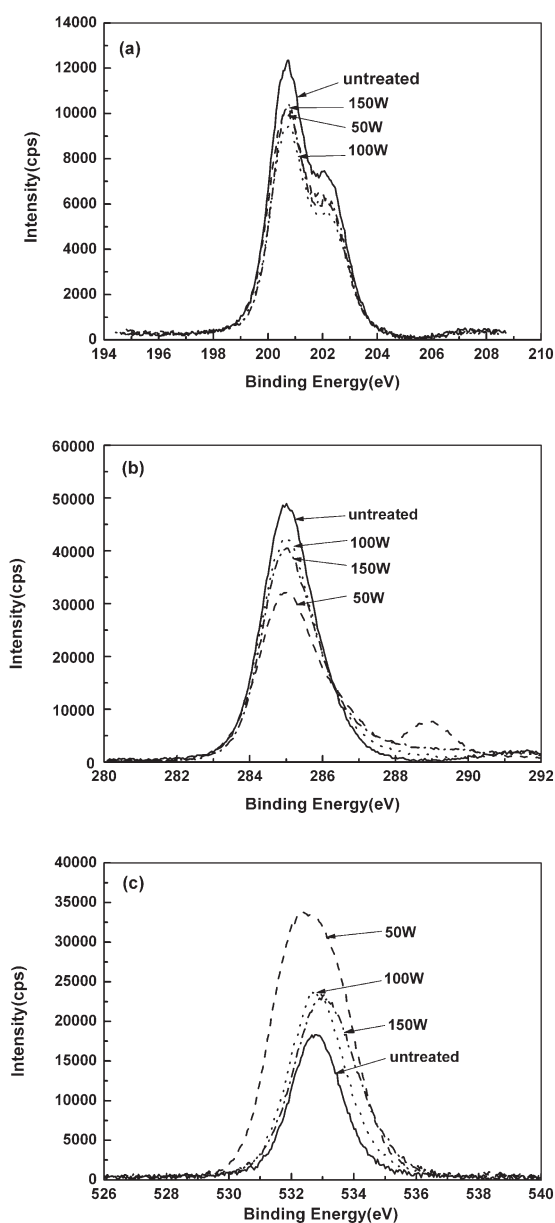


Figure 7 XPS wide-scan spectra of modified parylene-C films by plasma treatment at various RF powers in Ar/O₂ gas; (a) untreated; (b) 50 W; (c) 100 W; (d) 150 W.

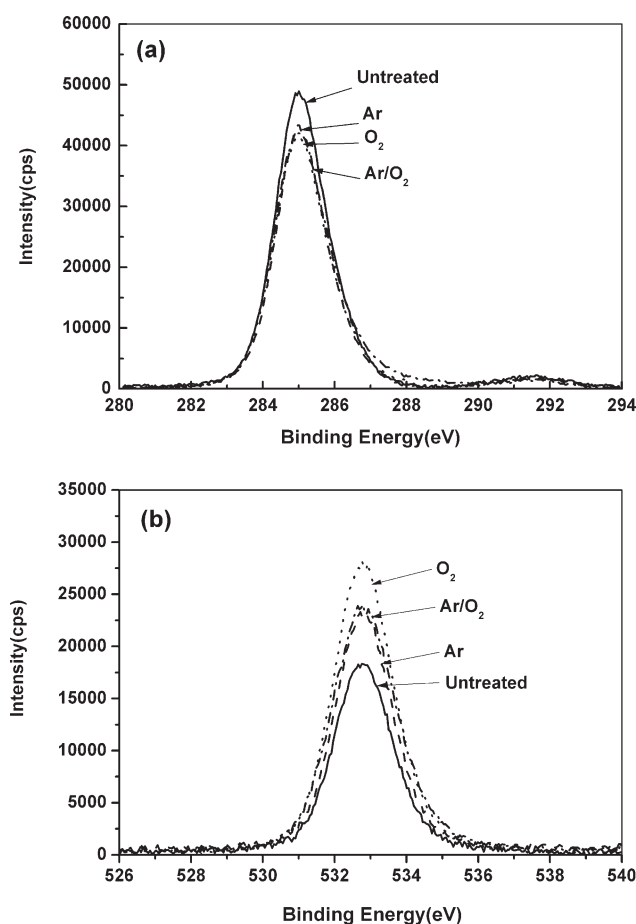


Figure 8 XPS spectra of modified parylene-C films by various gas types at RF power of 100 W: (a) C1s; (b) O1s.

the oxidation or substitution of functional groups from plasma treatment.

The XPS wide-scan spectra of parylene film before and after plasma treatments were measured, and it could be found that the RF power of plasma treatment affects the intensity of major peaks of C1s, O1s, and Cl2p, and the results are summarized in Figure 7. In comparing the parylene surfaces with and without plasma treatment using Ar/O₂ gas mixtures, the Cl2p peak intensity around 200 eV and the C1s peak intensity around 285 eV [Fig. 7(a,b), respectively] after plasma treatment became lower than before treatment, whereas the O1s peak intensity at 523.5 [Fig. 7(c)] became higher. It is because the oxygen from plasma becomes attached to sputtered chlorine atom sites during surface reactions. It can be confirmed from the XPS analyses that the new hydrophilic groups containing oxygen are formed near the parylene surface. Figure 8(a,b) show the C1s(a) and O1s peaks of XPS spectra of the parylene surfaces, when the different gases were used for the plasma process. After plasma treatment, the peak intensity of C1s decreased and O1s peak intensity increased for all the gases used, and this could

be conjectured from the possible chemical reactions occurring on the surface. With different gases, the oxygen plasma generated the highest intensity of O1s peak, whereas the other gases made similar O1s intensities. And the peak of C1s was nearly invariant with the type of the plasma gases used. From the IR analysis and XPS analysis showing the change of functional group on the surface of polymers interacting with plasma, the chemical reactions were considered to occur mainly on the surface due to the more frequent collisions between the plasma species and polymer surfaces.

Figure 9 shows the carbon and chlorine contents of parylene surfaces modified with Ar/O₂ plasma, which were obtained from the EDS analyses. It shows a strong relation between the RF power and the change of chemical structure by the surface reaction. When the higher RF power was employed in plasma treatment, the surface with higher chlorine content was obtained, whereas the carbon content of the surface became lower. This is quite coincident with the result from the XPS analysis, showing that chlorine atoms dissociate from the aromatic ring by the higher energy of the plasma imposed. It can be argued that the hydrophilicity of the coating surface should be controlled in a way quantitatively by changing RF powers.

Biocompatibility of the thin film of parylene after plasma treatment

Thus far, we investigated the major factors affecting the deposition process of parylene on the substrate and the effects of plasma treatment on the physicochemical properties of the parylene surface. Our final goal of this study is to derive the good biocompatible property of parylene for medical applications. Figure 10 shows the result of cytotoxicity

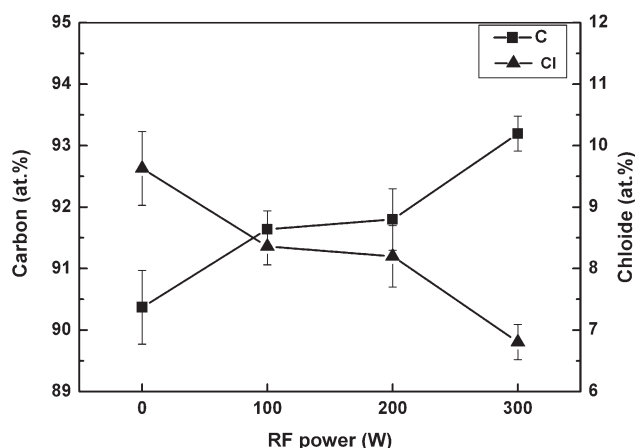


Figure 9 EDS analysis results of parylene-C film at various RF powers in Ar/O₂ gas plasma treatment.

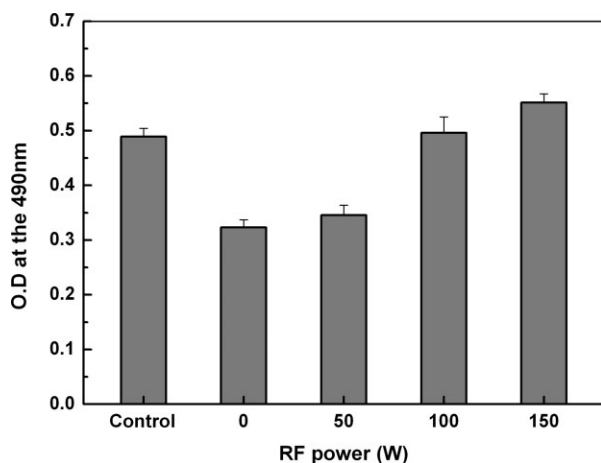


Figure 10 Effects of plasma treatment on the growth of HOS cells (4 days).

carried out with thin films of parylene with and without Ar/O₂ plasma treatment. The mean optical density at 490 nm indicates the number (the density) of cell. The control specimen was the Thermanox cover glass. If the control is set to 100%, the ratio of various cell contents of parylene films can be considered. The percentage then means the ratio of active cell proliferating in cytotoxicity test. The percentage of the cell in film as deposited was 66% belonging to the range of very limited proliferation rate of cell, whereas the cell percentage was 112.8% when the RF power was 150 W. The relationship between RF power and the cell proliferation is almost in linearity. It indicates that modified surfaces show improved cell biocompatibility, particularly when the RF power is over 100 W. That is, the minimum power (100 W) is required to improve the film properties via the plasma treatment. With too low kinetic energy of plasma species interacted on the surface, a collision between the plasma species and the surface does not lead to chemical reaction.²³ In our experiments, 100 W is critical to show the change of chemical structure on the parylene surface from the EDS analysis indicating the detection of new chlorine functional group on the surface and the improved cell biocompatibility of the resulting modified parylene film. The higher power leads no significant change of the trend. With too high power the damage of the parylene film was observed. From the morphology of cell group after culturing for 4 days on the thin film after plasma treatment, we could also confirm the proliferation of living cells in the sample after plasma treatment. The acceleration of the proliferation of cells after plasma treatment appears to be attributed both the improved biocompatibility and increased hydrophilicity of the film. The surface treatment itself also offers cleaning effect of surface. The increased hydrophilicity gives the good adsorption of the cells on the surface as an im-

portant factor for cell proliferation to provide cells with a good environment of surviving. The improved biocompatibility appears to result from the low disinfection effect of the film due to the decrease in content of asymmetric chlorine.

CONCLUSIONS

With a final goal to make an implantable medical device with various characteristics such as the resistance to water permeation, dielectric resistance, and improved biocompatibility, we attempted to obtain thin films of parylene-C with improved biocompatibility through plasma surface treatment. To determine the correlation between the process parameters and the final chemical or physicochemical properties of the film, thin films were prepared under different conditions of deposition and plasma treatment.

From the deposition process, when the deposition pressure increases, the deposition rate of parylene and the elongation of film increases, whereas surface contact angle and permeability, and the tensile strength of parylene film decreases. The breakdown voltage is affected by the roughness of substrate, and became very low when Ra value is higher than 0.5 μm . After a plasma treatment on the deposited parylene, the contact angle lowered sharply and the surface becomes more hydrophilic, since on the parylene surface are formed new hydrophilic groups from the treatment which causes oxygen atom to react with sputtered chlorine atom site.

When the RF power is above 100 W in plasma treatment with Ar/O₂ gas, the film retains good biocompatibility and low cytotoxicity. The acceleration of the proliferation of cells after plasma treatment appears to be attributed to the improved biocompatibility and hydrophilicity of the film offering cleaning effect of the surface as well as the low disinfection of the film and good adsorption of the cells on the surface.

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