



Tailoring polycarbonate surfaces for improved Ge film adhesion: The role of plasma treatments in 50:50 O₂/Ar atmospheres

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ABSTRACT

Polycarbonate (PC) substrates were exposed to plasma environments consisting of a 50:50 mixture of oxygen and argon, and were subsequently coated with germanium (Ge) films grown via sputtering. The hydrophilicity of the PC surfaces was tailored by ion bombardment with energy levels ranging from 50 to 300 eV, which led to a reduction in water contact angles from a native 80° to a superhydrophilic state. Analyses of chemical composition and structure of the PC were performed using X-ray Spectroscopy (XPS) and Fourier Transform Infrared Spectroscopy in Attenuated Total Reflectance geometry (FTIR-ATR), and then correlated to the adhesion of the Ge thin films. Optimal adhesion of the Ge films was achieved by bombarding the PC with ions at energies between 100 and 200 eV, activating the polymer surface while avoiding photodegradation as confirmed by chemical analysis. We report an efficient method for achieving superhydrophilicity of PC within a short treatment time of 60 s that can be effectively integrated in diverse vacuum applications.

1. Introduction

Sputtered germanium (Ge) films deposited onto polycarbonate (PC) hold potential in various industries such as infrared optics, telecommunications, photovoltaics, infrared sensors, and flexible electronics [1–3]. Such potential arises from the unique interplay between germanium's optical and electrical properties and the inherent versatility of polycarbonate among those industries. To use Ge films as functional coatings of PC, ensuring suitable adhesion is paramount. However, this adhesion can be challenging due to the mismatch in thermal expansion coefficients between the two materials. Furthermore, generally the poor wettability of PC could lead to compromised adhesion performance of sputtered films [4].

Studies examining the effects of plasma treatment on polymers have revealed significant alterations in their properties following plasma exposure [5–9]. These changes include surface morphology, chemical composition, etching, cross-linking, degradation, polymeric chain re-arrangement, and surface functionalization. By controlling the plasma composition, these treatments can be used to improve the adhesion of inorganic films [9–16]. Oxygen containing plasmas, for instance, may introduce C=O groups into the polymeric matrix, or break the polymeric chains replacing ester C–O with OH groups [16–19]. In contrast, plasmas of inert gases like argon typically lead to

an improved adhesion because the ions clean the surface or physically etch the material. Such improved adhesion results from two key factors: firstly, etching produces a rougher surface with a greater surface area, improving mechanical interlocking; secondly, removing surface contaminants ensures that coatings adhere directly to the substrate material instead of to a weak boundary layer. Plasmas containing oxygen and argon have been used to promote the adhesion of inorganic films such as Al, Ag, SiO₂, and Cu onto PC [20–23]. Despite the widespread application of plasma treatments for PC, studies evaluating their effect on Ge adhesion are not yet available in the scientific literature.

In plasma treatments of polymers, the DC self-bias voltage is a crucial parameter used to control the energy of the bombarding ions, which in turn may tailor the properties of the polymers exposed to the plasma. In the present work, we study the surface activation of PC substrates exposed to RF plasmas composed of 50% O₂ and 50% Ar, with the primary objective of tailoring the adhesion of Ge films. We explore the dependence of the wettability, chemical composition, and chemical structure of PC on the energy of the ion bombardment, which is controlled by the DC self-bias voltage registered at the electrode holding the PC substrates. This analysis is conducted through contact angle measurements, X-ray Photoelectron Spectroscopy (XPS), and Fourier Transform Infrared Spectroscopy (FTIR-ATR), and subsequently correlated to adhesion testing.

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2. Materials and methods

Makrolon® 2207 from Bayer (Leverkusen Germany) PC substrates was chosen because is a common material used in several industrial fields. The polymer, received in pellet form, was injection-molded into flat plates measuring $200 \times 100 \times 1$ mm. No mold-release agents were used during the injection process to avoid surface contamination of the PC. Subsequently, the substrates were immediately subjected to plasma treatment to further minimize the risk of contamination.

The PC substrates were treated in a prototype commercial reactor from Telstar Industrial S.A.® using plasmas produced in 50:50 Ar + O₂ atmospheres. A schematic of plasma reactor is shown in Fig. 1. The reactor was evacuated to a base pressure of 8×10^{-3} Pa, and then filled with a mix of O₂ (6 N purity) and Ar (6 N purity) to achieve a pressure of 4×10^{-1} Pa. The Ar and O₂ flows were adjusted to maintain a ratio of 50% of Ar and 50% of O₂. The plasma was generated with a RF power supply, while the DC self-bias voltage of the electrode holding the PC substrates was registered. The power was tailored to obtain a DC self-bias voltage output ranging between 50 and 300 V in 50 V increments. All plasma treatments were conducted for 1 min on three different PC substrates. Those conditions were specifically selected because they did not produce any visible defects on the surface of the polymer in preliminary experiments. Active cooling of the sample stage was not required, as the maximum observed temperature during the experiments was 60°C, well below the deformation threshold of the PC substrates.

The static water contact angles of the PC surfaces were measured using the sessile droplet method with a CAM200 optical contact angle and surface tension meter from KSV Instruments Ltd. The measurements were performed immediately before and after the plasma treatments to accurately evaluate their efficiency. The volume of the droplets was maintained at 1.2 ± 0.1 µL. Ten measurements were taken on different areas of the PC substrates to obtain average values for each bias voltage value.

The surface composition of the PC samples was studied using X-ray Photoelectron Spectroscopy (XPS) characterization in a PHI 5500 Multi-Technique System (from Physical Electronics). A monochromatic X-ray source (Al K α line, energy of 1486.6 eV, and power of 350 W) was positioned perpendicular to the analyzer axis and calibrated using the 3d5/2 line of Ag with a full width at half maximum (FWHM) of 0.8 eV. The analyzed area had a diameter of 0.8 mm. For the general spectra, the

selected resolution was 187.85 eV of Pass Energy with a step size of 0.8 eV/step. For the high-resolution spectra, a resolution of 23.5 eV of Pass Energy and a step size of 0.1 eV/step were used. The data was acquired after the plasma treatments to avoid surface contamination noise.

FTIR-ATR measurements of PC substrates were obtained using a Thermo-Scientific FTIR Nicolet 6700. The FTIR was equipped with a He/Ne laser and a DTGS detector. The measurements were conducted within the range of 700–4000 cm⁻¹ with a resolution of 0.97 cm⁻¹. A module, featuring a germanium crystal with $\theta_i = 45^\circ$, was used to analyze the smallest possible volume near the surface of the PC samples. In this configuration, the analyzed volume was determined using an online tool to calculate the penetration depth [24], which ranged from 180 to 560 nm for wavenumbers between 3800 and 1200 cm⁻¹, respectively. The spectra were acquired after the plasma treatments to avoid any features resulting from treatment aging.

To evaluate the influence of the surface activation of the PC substrates on the adhesion of Ge, the films were deposited without delay following the plasma treatments using a commercial D.C. magnetron sputtering system (Hartec Anlagenbau GmbH HD 550 550-MK3). The system was equipped with a 658.5×272.5 mm² polycrystalline Ge N-type target with 99.999% purity. The vacuum chamber was initially evacuated to a base pressure of 8×10^{-3} Pa, after which Ar was introduced to maintain a constant pressure of 1.5×10^{-1} Pa. Ge deposition was performed at 4 kW. The films were grown for 6 min to yield films with equivalent thicknesses among all samples. The samples were grown without intentional heating, and under the described sputtering conditions, the temperature was maintained below 40 °C. The adhesion of Ge films deposited onto PC substrates is evaluated using knives with 6 blades separated 1 mm apart from each other and an adhesive tape, following the UNE EN ISO 2409:2007 standard. To obtain the most accurate estimate of the percentage of delaminated material, photos of the cross-cut grids were taken and analyzed using Photoshop® [25] for pixel counting, as exemplified in Fig. 2. First, the contrast of the images was increased to enhance the differentiation between the cuts and the grid. Subsequently, the pixels corresponding to the cuts were removed from the image. Finally, a color elimination filter was applied. By counting the number of grey and white pixels in the resulting images, the delaminated area can be accurately estimated.

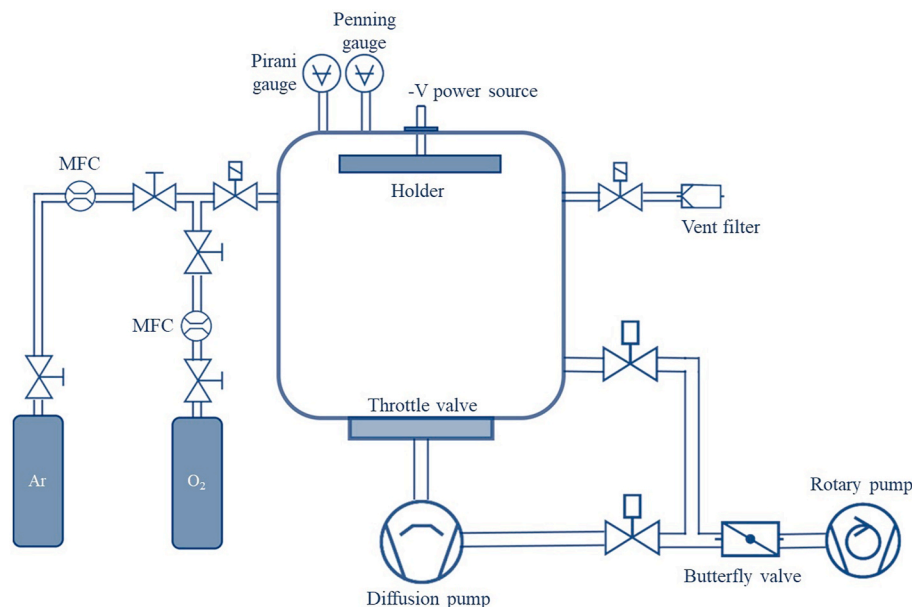


Fig. 1. Schematic of the plasma reactor used for the plasma treatments.

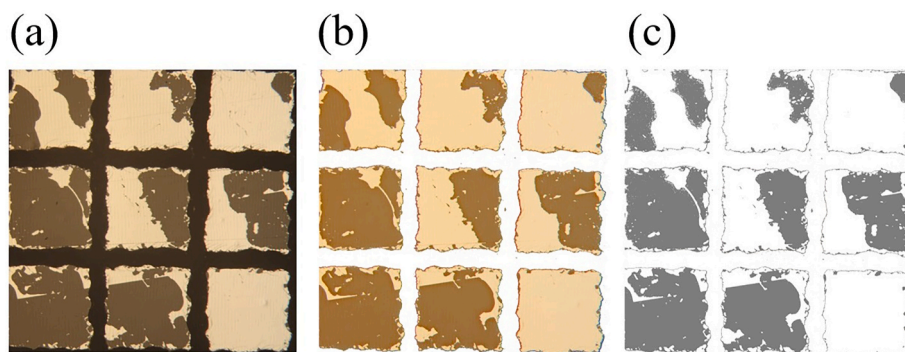


Fig. 2. Example depicting the pixel counting process performed to estimate the delaminated area of the cross-cut tests: (a) raw image edited to increase the contrast; (b) the pixels corresponding to the cuts are selected and eliminated from the image; (c) a filter is then applied to remove color, allowing for counting of the grey and white pixels.

3. Results and discussion

3.1. Effect of the plasma treatments on the wettability of PC

The average contact angle, as a function of the bias voltage for the PC surfaces directly exposed to the plasma treatments, is depicted in Fig. 3. The untreated PC exhibits a contact angle of 80° , which is similar to the 85° that has been previously reported by other authors [5]. The average contact angle decreases with the bias voltage, revealing surface activation of all PC surfaces following the plasma treatments in our study range. When plasma treatments were conducted at 300 V, the PC surface demonstrated superhydrophilic behavior i.e., the water did not maintain a droplet shape, making the contact angle measurement unreliable. Although the contact angle values were unmeasurable at 300 V, we have arbitrarily assigned a value of 3° to that point for ease of data presentation. While superhydrophilicity in PC has been previously reported, the plasma treatment at 300 V for 60 s has proven to be highly efficient. To the best of our knowledge, no previous study has reported a method to achieve such a phenomenon in PC after treatment exposures of 60 s or less [7,10,26–36]. Such plasma treatment can be effectively integrated as an additional, efficient step within other vacuum processes in diverse applications.

3.2. Effect of plasma treatments on the surface chemistry of PC substrates

The structure of the polymer was primarily composed of oxygen and carbon, with small traces of Si, Na, and Al. These traces were not

considered in the analysis of the XPS results to simplify the calculation of composition. The untreated PC substrates had about 7% oxygen content, lower than the reported 15% [35–37]. Surface contamination or injection processing conditions may explain the discrepancy. Fig. 4 shows the O/C ratio as a function of bias voltage. Plasma treatment altered the chemical composition of the surface of PC, confirming surface oxidation resulting from plasma exposure. Oxygen was incorporated onto the polymer surface as bias increased, eventually saturating around $O/C = 0.30 \pm 0.04\%$ for $V \geq 150V$. The results additionally revealed fluctuations in the O/C ratio as the bias voltage increased. These fluctuations may be attributed to a range of factors, including sample inhomogeneities, the uniformity of plasma treatment, and the presence of small, heterogeneously distributed traces of surface contaminants on the PC substrates.

The deconvolutions of the O 1s and C 1s core level spectra of the PC samples are presented in Figs. 5 and 6, respectively. To ensure an accurate analysis, a correction step was implemented using a Shirley background subtraction prior to each fitting process. The deconvolution of each spectrum was obtained using Gaussian curves.

The O 1s and C 1s spectra of the untreated PC samples exhibited the characteristic features of the polymer, as reported by other authors [10, 35]. The O 1s spectra revealed two broad peaks corresponding to C–O and C=O species at 532.4 and 534 eV, respectively.

The C 1s spectra revealed the presence of two broad peaks centered around 284.8 and 290.7 eV. The peak centered at 284.8 eV was primarily composed of a mixture of C–C, C–O, and C=O carbon species. The analysis confirmed that the band around 290.7 eV is composed of

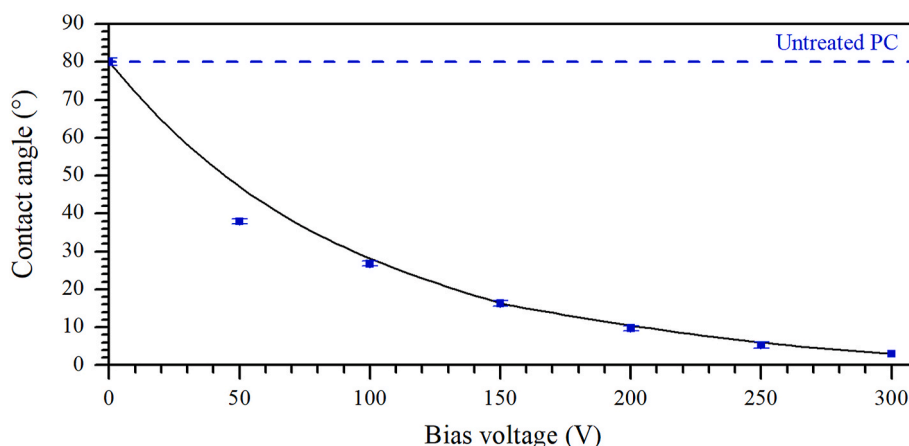


Fig. 3. The average contact angle of the plasma-modified PC substrates was plotted as a function of the bias voltage. The error bars were obtained by calculating the standard deviation of ten measurements performed for each bias voltage value. The dashed blue line represents the average contact angle measured on the untreated PC, while the black line has been included as a visual aid.

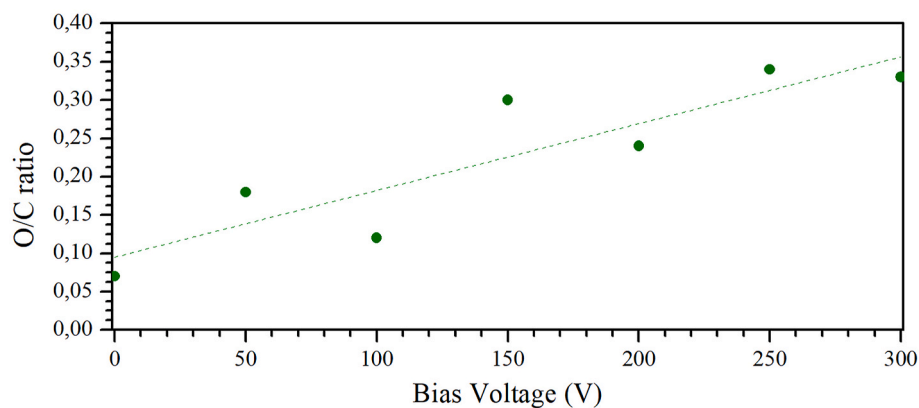


Fig. 4. O/C ratio as a function of bias voltage. This ratio is calculated based on the atomic content obtained from the intensities of the photoelectron peaks C 1s and O 1s. The green dashed line, serving as a guide for the eye rather than an analytical fit, highlights the trend of oxygen incorporation with increasing bias voltage.

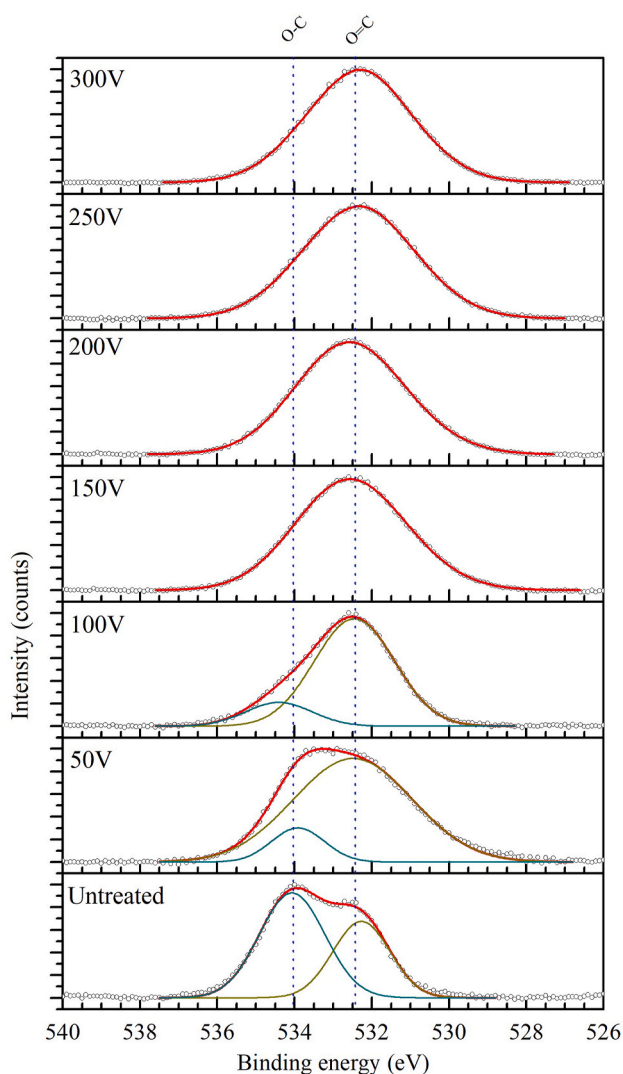


Fig. 5. Deconvolution of the O 1s spectra as a function of bias voltage. The vertical dotted lines represent the position of oxygen related species.

two distinct contributions: carbon within the carbonate group, centered at 290.5 eV, and the π - π^* transition (shake-up) related to the phenyl ring, centered at 292.03 eV. Notably, the C-O peak is not observed within the 50–100 V range, unlike in the O 1s deconvolution. This may

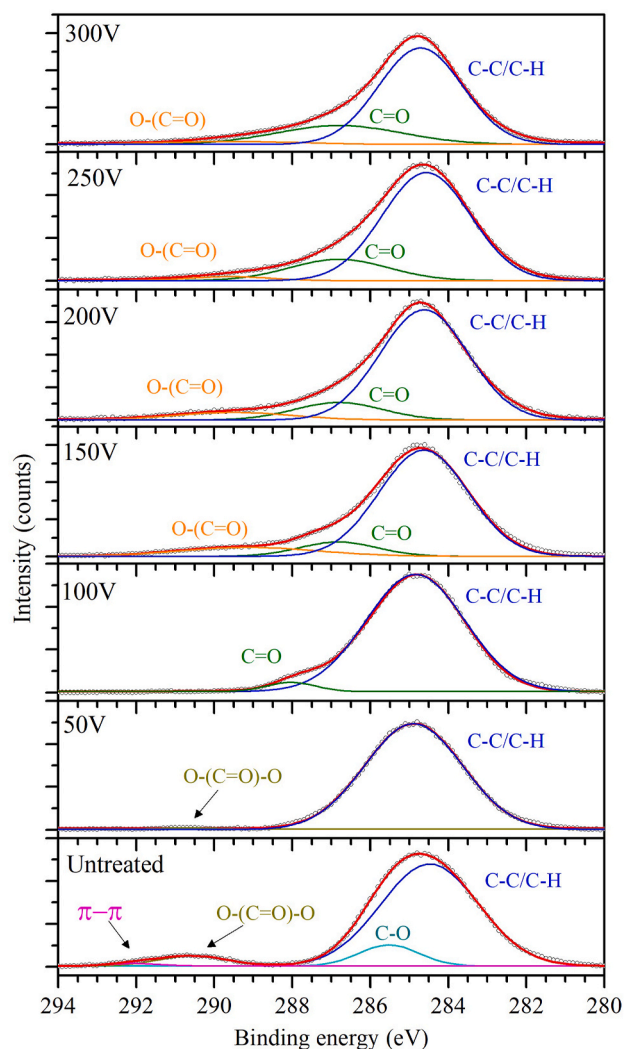


Fig. 6. Deconvolution of the C 1s core level spectra as a function of bias voltage.

be due to its subtle contribution, which could go unnoticed in the face of the more prominent C-C peak, as suggested by the O=C/O-C ratio and the weak presence of O-(C=O)-O detected in both the O 1s and C 1s deconvolutions. The curve-fit of the samples treated at a bias of ≥ 150 V revealed an additional peak centered around 288.6 eV. This peak could

potentially be related to O–C–O or O–(C=O) species [30]. However, the O 1s results suggest that an O–(C=O) contribution is more probable, as the O–C peak is indistinguishable in those samples.

A clear correlation is observed between the plasma treatments and the introduction of O=C polar groups, as evidenced in the O 1s deconvoluted spectra. Increments in bias voltage led to a greater presence of O=C species, reflected in an increase of the O=C peak area. Conversely, the O–C species displayed a decreasing trend with bias voltage, accompanied by both a widening and a shift towards higher binding energy values in the O–C peak. These results suggest disorder and may indicate the existence of multiple environments surrounding the O–C species. When treatments were conducted above 100 V, the O–C peak was not detected. This absence could be attributed either to the lack of O–C bonds or to a high content of O=C bonds, which might potentially mask the presence of the O–C contribution.

Fig. 7 depicts the peak area of the C 1s deconvoluted peaks as a function of bias voltage. The plasma treatments led to a significant modification in the chemical binding state of the C 1s spectra of the plasma-modified PC. The data suggests that ion bombardment played a crucial role in determining the bindings changes observed, with two distinct observable stages: low energy bombardment for bias voltages up to 150 V, and high energy bombardment for bias up to 300 V.

At low-energy bombardment, oxygen was incorporated, as revealed by the increased proportion of C=O species in comparison to C–O. As the bias voltage increased, a shoulder attributed to C=O-related species emerged in the C 1s core level spectra, while C–O species were undetected. At 150 V, C=O-related peaks widened, and their areas increased significantly implying a wide distribution. Additionally, it's worth mentioning that the shake-up peak related to the aromatic phenyl ring disappeared after plasma exposure at this stage, regardless of the bias voltage. This supports the hypothesis that oxygen incorporation during plasma exposure is somehow capable of breaking the phenyl ring, as previously suggested by Tompkins et al. [38].

The high-energy bombardment stage is characterized by the sputtering of material. At this point, Ar ions remove atoms from the polymer, leading to chain scission. Despite this, the results indicate that oxygen continues to be incorporated into the polymeric chains. The competition between oxygen incorporation and atom sputtering is complex, with the C=O related peaks widening at this stage. This widening indicates

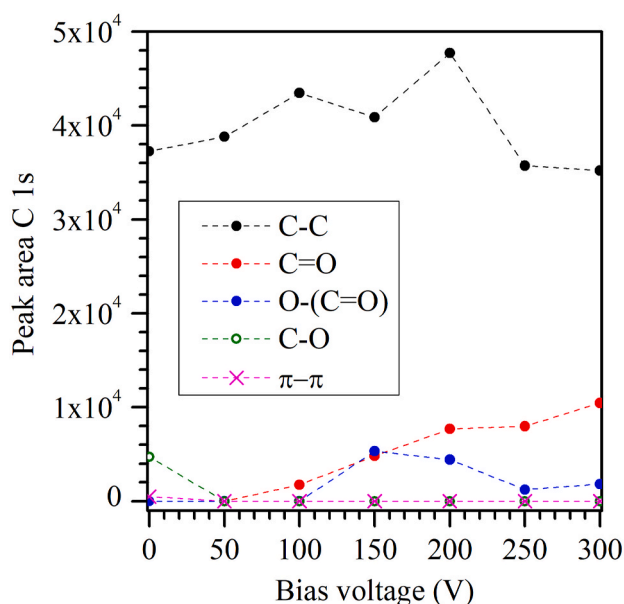


Fig. 7. Peak area of the C 1s peaks versus bias voltage. The dashed lines are a guide to the eye. The characteristic C–O and π - π shake-up peaks of polycarbonate disappeared after the plasma treatments.

disorder and multiple possible environments for the C=O bonds. In fact, the O=C species did not pre-exist as stable states in PC, but were produced as functional groups by the plasma treatment when the bias voltage fell within this stage. The presence of the functional groups containing C=O related species could explain the increased wettability observed in the contact angle measurements, as the surface energy of polymers increase with introduction of polar moieties [10]. Alongside these results, the area of the C–C/C–H peak for samples subjected to biases ≥ 250 V decreased. This finding is consistent with composition calculations, as these samples exhibit the lowest carbon content.

3.3. Effect of plasma treatments on the molecular structure of PC substrates

The FTIR-ATR spectra are shown in Fig. 8. The spectra presented the characteristic absorption bands of C–O stretching between 1163 and 1227 cm^{-1} , stretching of the carbonyl (C=O) bands at 1774 cm^{-1} in the carbonate group. Bands associated to the phenyl aromatic ring vibrations are found for the stretching of C=C at 1505 cm^{-1} and C–C around 1600 cm^{-1} . Around 1730 cm^{-1} a shoulder related to carbonyl in aromatic ester groups is detected [39], which are not native in PC but most likely result of incomplete formation of PC chains due to a missing oxygen between a phenyl ring and the carbonate group. Bands related to C–H stretching modes of the isopropylidene group are found between 3100 and 2800 cm^{-1} . The peak at 3540 cm^{-1} corresponds to OH related groups at the chain-ends of polymer, while the band 3673 cm^{-1} is associated to adsorbed water [40–43]. Two small peaks at 2232 and 2199 cm^{-1} are observed. Those small peaks are not typical of PC but may be attributed to NH-containing groups.

Plasma exposure significantly impacts the molecular structure of the PC, as observed in Fig. 8. High-energy treatments provoked a broad and intense band centered at 3695 cm^{-1} that obscured the adsorbed water-related band at 3673 cm^{-1} , making it indistinguishable. This band is likely a result of hydrogen bonding between molecules containing OH functional groups [44]. Notably, the CH₃ stretching region appeared to remain unaffected, ruling out chain scission of the isopropylidene group as a potential degradation mechanism [45]. In the fingerprint region the plasma treatments had a minor impact. The C–O stretching peaks exhibited some kind of dependence on plasma exposure, although the data did not clearly show a correlation with the treatments' energy.

Fig. 9 presents the 1900–1600 cm^{-1} region of the FTIR spectra. The carbonyl peak at 1774 cm^{-1} remained constant within the bias range of 0–200 V. However, for bias voltages ≥ 250 V, the intensity of the peak slightly decreased with increasing bias. Additionally, the ester-related

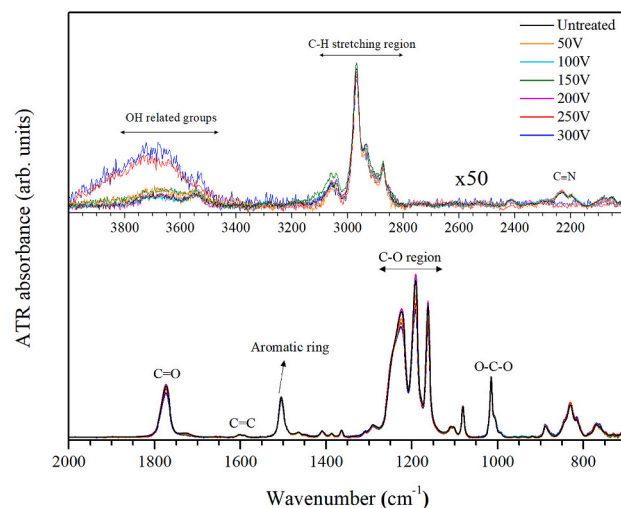


Fig. 8. FTIR-ATR spectra of the PC substrates within the 4000–2000 cm^{-1} range multiplied by a 50 factor (up), and the 2000–700 cm^{-1} range (down).

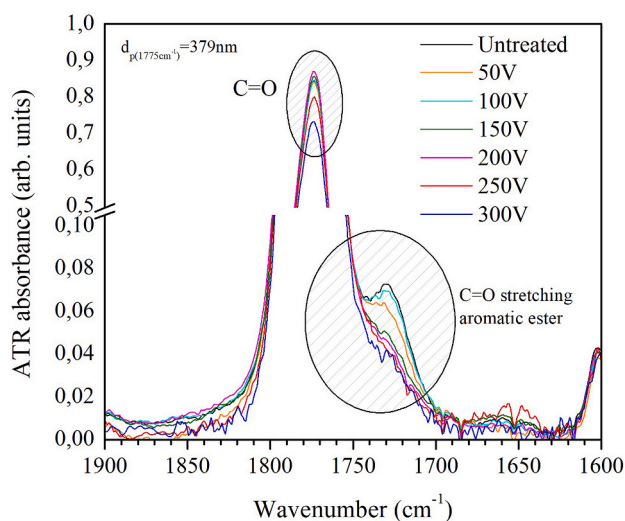


Fig. 9. Absorbance FTIR-ATR spectra of the carbonyl group for the different plasma conditions. An axis break has been introduced for ease of the analysis of the peak's intensity at 1774 cm^{-1} and the small shoulder around 1730 cm^{-1} . The penetration depth of the infrared radiation is also shown.

shoulder decreased increasing bias, becoming almost imperceptible for bias values above 150 V. This result suggests that the ester groups are preferentially broken during plasma exposure. Correspondingly, the shift towards higher wavenumber values may be explained by mass loss due to such breakage.

The mechanism underlying the changes in PC structure caused by plasma treatments is complex, involving factors such as ion bombardment and UV light irradiation. On the one hand, our observations point towards a photolysis degradation mechanism triggered by UV radiation, a process consistent with previously described photodegradation patterns [46] and illustrated in Fig. 10. FTIR-ATR results indicate that degradation of the PC occurs when subjected to high-energy plasma treatments, with oxygen-containing molecules being preferentially damaged. This degradation manifests as a decrease in peaks at 1774 cm^{-1} and around 1200 cm^{-1} , corresponding to the breakdown of the C=O and C-O components in the polymer's carbonate backbone, respectively. The breakdown of these groups leads to the formation of radical sites, which then may undergo hydrogen abstraction to form OH groups. The increase in OH groups is confirmed by the broad intense band around 3700 cm^{-1} , an indicative of hydrogen bonding between OH groups and other polar molecules within the polymer, such as the remaining carbonyl groups in the carbonate structure. The variation in penetration depth for our FTIR-ATR analysis, ranged from 180 nm at a wavenumber of 3800 cm^{-1} to 560 nm at 1200 cm^{-1} , which confirms that

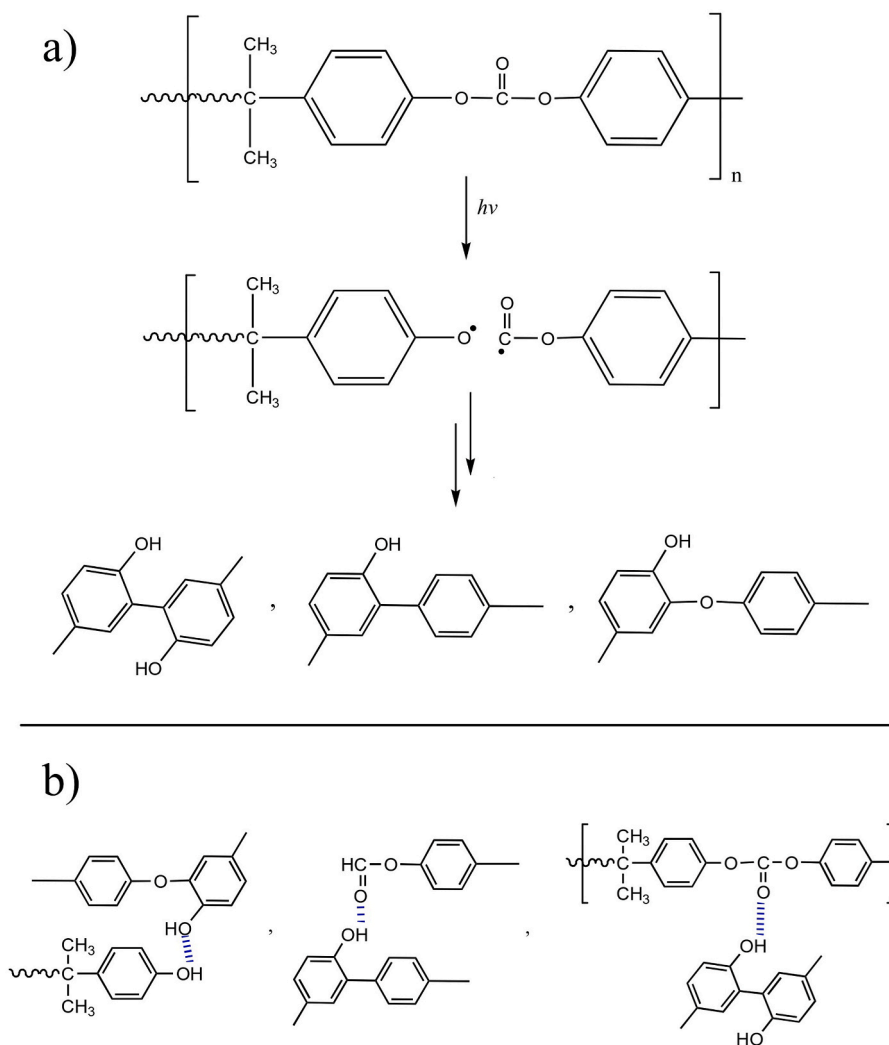


Fig. 10. Scheme of photodegradation via direct photolysis in the plasma treated PC substrates. (a) Chain scission in the carbonate group: free radical formation, hydrogen abstraction, and subsequent recombination. (b) examples of hydrogen bonding between OH groups and other polar molecules within the polymer.

the photodegradation is occurring deep within the polymer's volume. Such finding aligns with the observations made in other studies, which indicate that photolysis due to short-wavelength UV radiation is predominantly a reaction affecting up to a depth of 3 μm [47]. On the other hand, to evaluate the potential contribution of ion bombardment during plasma exposure we simulated the trajectory of ions accelerated at 300 eV towards polycarbonate using SRIM (Stopping and Range of Ions in Matter) software [48]. The results, depicted in Fig. 11, showed that the ions reach a maximum penetration depth ranging between 4 and 6 nm. Therefore, introduction of oxygen and chain-scission through ion bombardment predominantly occurs in the near-surface region of the polymer. In summary, our results support the conclusion that the primary cause of the observed changes in the PC subjected to high-energy plasma treatments is photodegradation triggered by UV radiation.

3.4. Influence of plasma treatments on the adhesion of Ge films to modified PC substrates

The delamination area of Ge as a function of bias voltage is presented in Fig. 12. The adhesion of the Ge films showed a dependency on the bias voltage of the plasma treatments, with two clear different tendencies depending on the bias range. The first tendency is observed in the 0–200 V range, where the adhesion of Ge improves as bias increases. Initially, the adhesion of Ge deposited onto untreated PC is poor, exhibiting an adhesive failure around 17% of the total evaluated area. However, for plasma treatments performed at 50 V, the delaminated area decreased from 17% to 4%, showing adhesive failure only at certain grid intersections. For biases between 100 and 200 V, no sputtered material was detached from the surface of the PC, regardless of the energy of the treatment.

The second tendency is observed for plasma treatments at bias between 250 and 300 V. The delaminated area started to increase with bias voltage increments. For treatments performed at 250 V the delaminated area slightly increased 1%, while for the most energetic treatment, the delaminated area nearly returns to the original values of the untreated PC. Although our data does not provide sufficient evidence to definitively determine whether the delamination is due to cohesive failure within the substrate or detachment of Ge, the former seems more likely. This hypothesis is supported by the observed carbon loss and in-depth degradation in the samples treated for bias ≥ 250 V, as depicted in the XPS and FTIR analyses.

Adhesion of Ge on PC correlates with the increasing wettability observed in contact angle measurements, as previously reported for other inorganic materials deposited onto polymers [15,35,49]. Although our study suggests that the introduction of oxygen-containing functional groups on the PC surface, as observed in XPS, promotes both the wettability of PC and the subsequent adhesion of Ge, the results from the

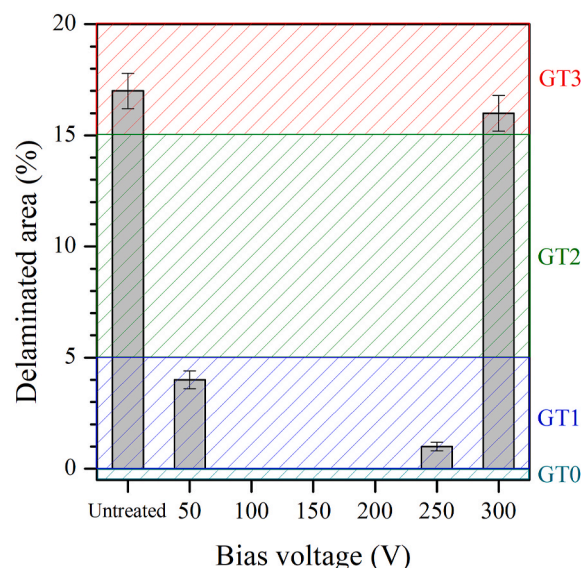


Fig. 12. Delamination area of the Ge films from the PC substrate versus bias voltage of the plasma treatments. Colored areas filled with the diagonal pattern represent the GT ranking according to DIN ISO 2409.

FTIR analysis do not entirely support the observed Ge delamination. A certain degree of degradation was evident in cases where only 1% of the material delaminated. The data collected do not provide a means to quantify the effect of plasma treatments on polymer degradation, which limits any correlation between degradation and the delaminated areas observed in cross-cut testing. According to our data, adhesion or cohesive failure may still occur even if some degree of polymer degradation is present. Surface roughness analysis could be of significant interest for future research for a deeper understanding of the adhesion of Ge films under scenarios where slight PC degradation is still compatible with suitable Ge adhesion. Regardless, our findings indicate that super-hydrophilic behavior attained under plasma exposure in 50:50 O₂/Ar atmospheres, serves as a reliable empirical marker aiding in the prevention of over treatment, and in optimizing the adhesion of Ge films on plasma treated PC.

4. Conclusions

Adhesion of sputtered Ge films deposited onto PC substrates can be effectively adjusted by controlling the DC self-bias voltage established during exposure to a plasma environment in a 50:50 oxygen/argon atmosphere. Optimal adhesion of Ge films can be achieved by irradiating

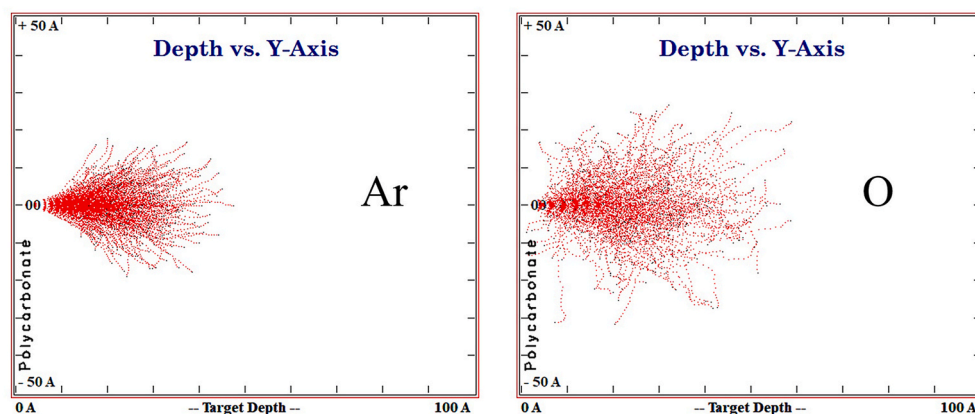


Fig. 11. Simulation of the bombardment of PC by Ar and O ions accelerated at 300 eV, depicting their trajectories with penetration depths of ~ 4 nm for Ar (left) and ~ 6 nm for O (right).

polycarbonate with Ar and O ions at energies between 100 and 200 eV, which functionalize the polymer surface while avoiding photodegradation.

Through a combination of XPS and FTIR analysis, we have established that ion bombardment and UV radiation play distinct roles. The former introduces polar functional groups on the surface of the polycarbonate, while the latter triggers the breakage of those very same species within the volume of the polymer. Although the underlying mechanisms governing surface and volume transformations might be complex, superhydrophilicity can serve as a marker to identify the balance between these phenomena to optimize Ge film adhesion.

The research demonstrates the applicability of 50:50 balanced oxygen/argon plasma treatments in achieving optimal functionalization of PC prior to Ge film deposition in sputtering processes. The oxygen/argon plasma treatments can be effectively integrated as an additional, efficient step within sputtering processes to be implemented in diverse industrial applications.

We report an efficient method for achieving superhydrophilicity of polycarbonate within a short treatment time of 60 s by controlling the ion bombardment energy to 300 eV in a plasma environment composed of a 50:50 oxygen/argon mix.

CRediT authorship contribution statement

J. Peralta: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **J. Esteve:** Formal analysis, Investigation, Project administration, Supervision. **A. Lousa:** Conceptualization, Formal analysis, Investigation, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. . Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijadhadh.2024.103691>.

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