

Polyurea MLD using low melting point precursors and a possible method of testing suitability for protein crosslinking

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Abstract

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Molecular layer deposition (MLD) is a growing area of research and identifying ideal, easy-to-use precursors is an important goal in furthering the field. An ideal precursor has certain qualities: low cost, high vapor pressure, compatibility with a range of temperatures that allow for low temperature processes with sensitive substrates, reliable, predictable growth characteristics such as a linear relationship between film thickness and cycle count, and exponential saturation of the surface with precursor exposure characteristic of the self-saturating nature of the idealized MLD process. This work demonstrates an MLD process for depositing polyurea films using 2,4-toluene diisocyanate (TDIC) and ethylene diamine (ED), which can be favorably compared to the more common polyurea deposition of 1,4-phenylene diisocyanate (PDIC) and ED in terms of cost, vapor pressure, and low temperature performance. The process described here has nearly identical growth characteristics, making it an ideal stand-in for existing polyurea MLD applications. The similarities support the termination-diffusion model described in earlier work¹, and the polyurea film is further assessed for its suitability for use in protein immobilization by demonstration of its free amine surface functionality and measurement of its zeta potential.

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Introduction

Molecular layer deposition (MLD) is a vapor phase process for depositing ultrathin polymer films onto a surface. During an MLD process, a precursor, typically a homobifunctional monomer, is introduced into a reaction chamber and allowed to react with a surface. Excess reactant is then removed from the chamber using a vacuum or inert purge gas before repeating this exposure step with one or more mutually reactive precursors, which together make up one cycle of the process. These steps can then be repeated for the desired number of cycles to grow films with sub-nanometer thickness and compositional control. MLD continues to see development, and thus far, a variety of materials have been deposited using this approach, ranging from polyamides, to PEDOT, to fluorocarbons, and metal-organic films.²

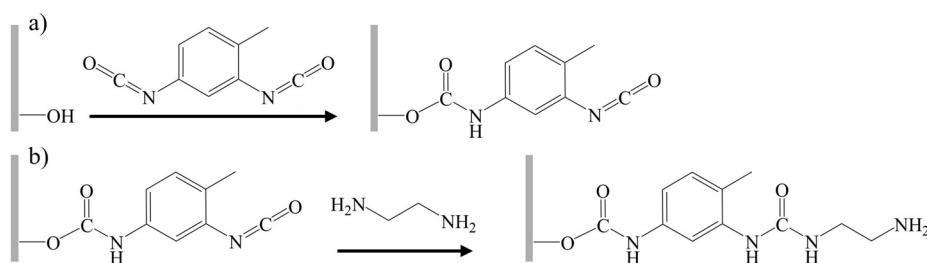


Figure 1 The reaction of TDIC with the surface hydroxyl groups of silicon dioxide

Polyurea MLD, in particular, is a well-studied process, in part due to its relative ease of deposition. Though a variety of monomers have been explored for creating polyurea,² the most well-documented set of precursors for this reaction is 1,4-phenylene diisocyanate (PDIC) and ethylene diamine (ED).^{1,3-6} However, PDIC is a solid at room temperature. Solid precursors can condense in cold spots within the chamber, which can clog valves and force reactor cleaning steps, and may result in faster degradation of the precursor.⁷ Heating the reactor can help avoid this condensation, but MLD processes have an inverse relationship with heat and growth rate⁴ and some applications may not permit elevated temperatures. For these reasons, migrating away from this precursor to a liquid precursor would be beneficial. One interesting alternative to PDIC is 2,4-toluene diisocyanate (TDIC). TDIC is the second largest production volume isocyanate compound globally, accounting for 34% of all isocyanate produced annually and is the major product formed by the di-nitration of toluene, an easier, faster, and higher yield process than the di-nitration of benzene (the yield is 65-80% 2,4-TDIC and 20-35% 2,6-TDIC, but TDIC refers to exclusively 2,4-TDIC in this work).⁸⁻¹¹ As such, TDIC is significantly less expensive and more well characterized than PDIC. Notably, the presence of a methyl group and the positioning of the isocyanate groups breaks the symmetry of the compound, which results in a lower melting point⁸ of 21 °C and a vapor pressure of ~10mTorr at 25 °C,¹² qualities which are highly desirable for an MLD precursor.

In this work, we demonstrate an MLD process using TDIC and ED, which is shown to have a similar growth per cycle (GPC) and saturation times for the isocyanate/diamine precursors (3.9Å/cycle and 150/20s, respectively, in this work) when compared to previous PDIC/ED processes.^{1,3-6} We collect FTIR and XPS spectra to confirm the composition of films produced using these precursors. As a preliminary assessment of the film's suitability for other applications, we further measure the film's surface functionality and zeta potential. This work ultimately demonstrates one method for selecting easier-to-use precursors for the MLD process.

Results

Growth characteristics. To test the ability of TDIC to function as a polyurea MLD reactant, polyurea films were grown directly on Piranha-etched silicon wafers, and the thickness of the resultant films was measured using

ellipsometry (Figure 2). Thickness measurements of the film on silicon wafers (Figure 2a) show that the process is linear up to 50 cycles at a rate of $3.9 \pm 0.1 \text{ \AA/cycle}$. Previous work has reported that isocyanate can react with hydroxyl groups on the silicon surface^{7,13,14} and it is assumed that the same happened here

Saturation behavior of the ED and TDIC reactants is shown in Figures 2b and 2c, respectively. In an ideal MLD process, the homobifunctional precursors would react once with the surface and leave one functional group unreacted, available to react with the complementary precursor. In this ideal reaction cycle, the maximum GPC is achieved when surface saturation is reached during each precursor exposure. To determine the dose time required to reach ED saturation, TDIC was dosed for 150s while the dose time of ED was varied between 0 and 45s. Thickness measurements show ideal saturation behavior, exponentially approaching a maximum of $3.8 \text{ \AA/cycle}$ by ~ 20 s of ED exposure. Similarly, to determine the dose time required to reach TDIC saturation, ED was dosed for 17s while the dose time of TDIC was varied between 0 and 600s. The TDIC saturation curve shows “soft” saturation behavior (Figure 2c), which has previously been observed for MLD^{1,7,13} and ALD/MLD¹⁵ processes. It is hypothesized that diffusion of a precursor into the film results in some CVD type growth as that precursor outgases. The GPC at 150s, where there is a rapid change in slope, is taken to be approximately equal to the “strictly MLD” component of the GPC. Continued increases in the GPC after this point are attributed to CVD, although deconvoluting the contributions of MLD and CVD to the total GPC requires further experimentation.^{4,15}

Note that the data in Figure 2a was collected using TDIC and ED doses in excess of the critical dose time required to achieve surface saturation, which may account for the excess GPC compared to those seen in the saturation curves. Until the CVD component is fully eliminated from the MLD recipe, the true “strictly MLD” GPC cannot be known, but the CVD contribution may be significant.¹⁵

In previous work with PDIC and ED, linear GPCs around $4.1 \text{ \AA/cycle}$ were observed up to 50 cycles and saturation behavior was achieved after 200 and 20s, respectively⁴. These growth characteristics are remarkably similar, despite the 120° angle between the isocyanate groups of TDIC (vs 180° in PDIC). This supports the termination-diffusion model of MLD growth, in which the growth of the film is independent of the growth angle. In this model, the homobifunctional polymers occasionally react twice with the surface and linear GPC is the result of a balance between these double reactions and precursor diffusion into the film. Polymer chains are continually terminated and re-started, which minimizes compounding effects of the polymer bond angle.^{1,7} Ultimately, the similarities between the growth characteristics of the TDIC/ED and PDIC/ED systems suggest that the easier to use TDIC precursor is an attractive alternative to PDIC.

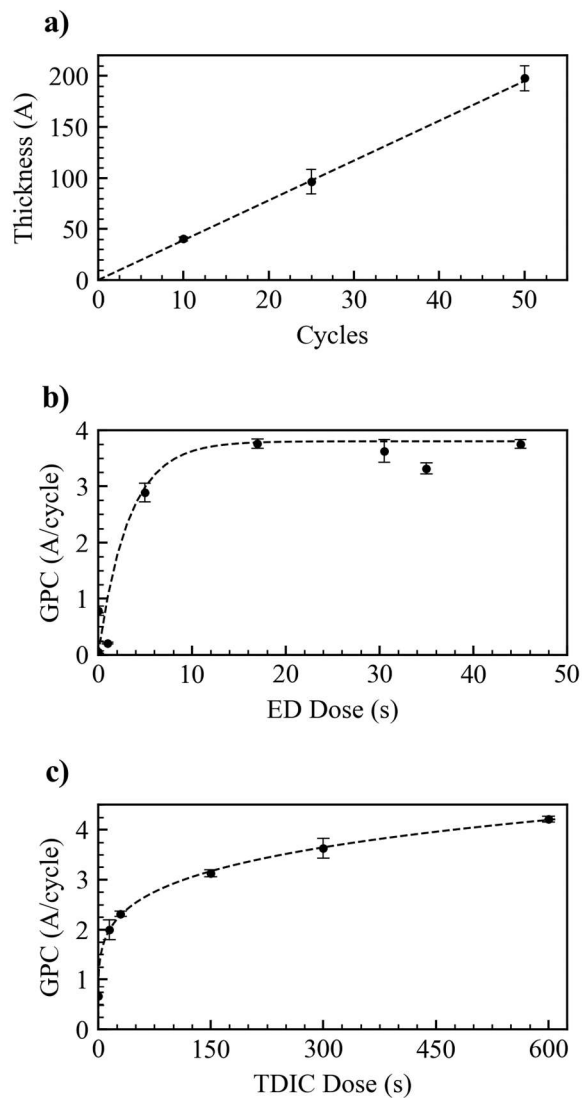


Figure 2 a) the growth rate of the film b) & c) the saturation curves of ED and TDIC, respectively

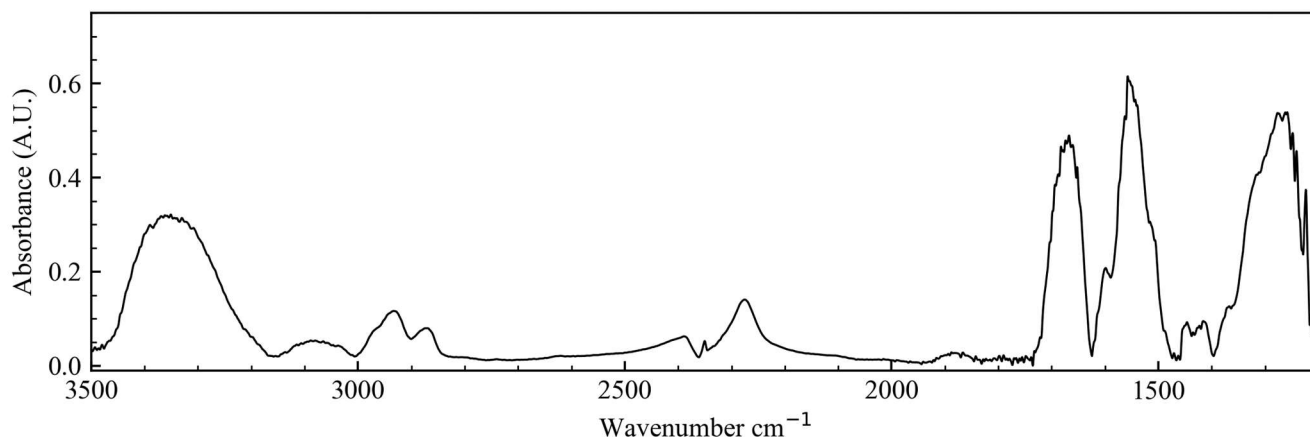


Figure 3 The FTIR spectra of the film on silica powder

Fourier Transform Infrared Spectroscopy (FTIR). To verify the successful reaction between TDIC and ED, an MLD film $\sim 370\text{\AA}$ thick, based on the film thickness deposited on an included silicon wafer, was deposited on silica powder and analyzed with FTIR spectroscopy. The results of this analysis are shown in Figure 3. Broad features are observed, which are attributed to extensive hydrogen bonding in the bulk material and are consistent with polyurea formation. The peaks at 1667cm^{-1} & 1557cm^{-1} are assigned to the Amide I & II peaks, as has been done previously⁴, which suggests the successful reaction between TDIC and ED. The other peaks are assigned as follows: the peak at 3358cm^{-1} is assigned to the N-H stretching mode.¹⁶ The peaks at 2933cm^{-1} and 2873cm^{-1} are associated with the stretching mode of aliphatic CH_2 groups.^{17,18} The peaks at 1435cm^{-1} and 1277cm^{-1} as assigned to the C-C ring and C-N stretching mode mixed with aromatic ring stretching modes, respectively.⁷ The peak at 2275cm^{-1} is assigned to residual isocyanate ($\text{N}=\text{C}=\text{O}$),^{7,19} which is seen in the aqueous preparation of bulk polyurea,¹⁹ though notably not in the spectra of MLD polyurea films deposited on silicon wafers in other work in the literature.^{4,7,13} This may suggest that a high concentration of TDIC was adsorbed onto the silica powder and trapped beneath a CVD film, shielding it from reaction with both ED and atmospheric H_2O

X-ray photoelectron spectroscopy (XPS). The composition of the films was further characterized using XPS analysis on five polyurea coated silicon wafers produced in a single run. A survey scan (Figure 4a) shows an

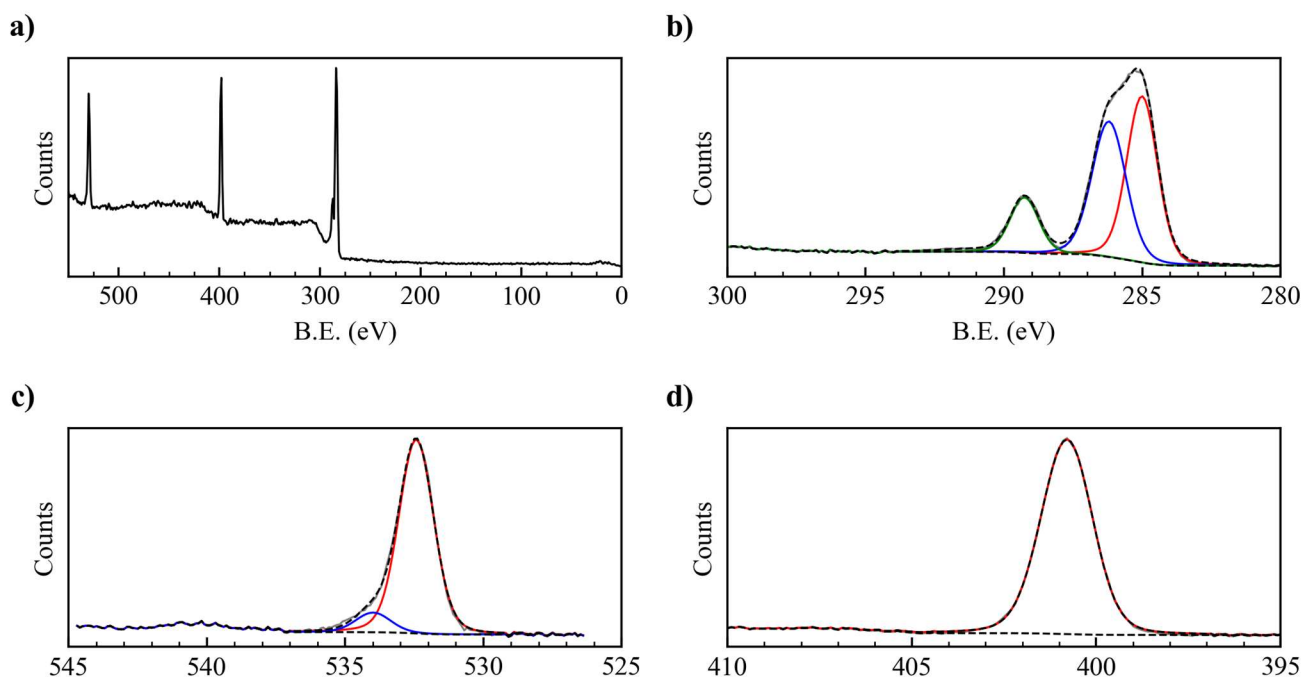


Figure 4 Representative scans selected out of a sample size of 5. a) survey scan, b) fine scan of oxygen, c) fine scan of nitrogen, d) fine scan of carbon. Note that the BE of C1s at 285.00 in d) is used as a standard for charging

absence of a silicon peak around 100eV, indicating that the films are too thick to observe the silicon surface. The average atomic ratio observed across the five samples is measured to be 7:2:1 C/N/O. Given the theoretical atomic ratio of this polyurea film (C₁₁N₄O₂) is 5.5:2:1 C/N/O, this result is consistent with the expected polyurea, with the excess carbon attributed to adventitious carbon.

Fine scans of N, O, and C also appear as expected for polyurea. The N 1s peak at 400.4 eV (Figure 4c) is attributed to amide nitrogen, the O 1s peak (Figure 4b) at 532.0 eV is attributed to carbonyl oxygen, and the shoulder of the O 1s peak at 533.4 eV is attributed to an O 1s shakeup.²⁰ The C1s fine scans (Figure 4d) show three peaks located at 285.0, 286.2, and 289.3 eV, which are attributed to the aliphatic, aromatic, and carbonyl carbons in the structure, respectively. The theoretical ratio of these three types of carbons is 1.5:3:1, respectively, but a ratio of 3:3:1 is seen. The excess aliphatic carbon is similarly attributed to adventitious carbon.^{21,22}

Suitability testing. One potential use of MLD is for creating a surface coating to bind proteins.²³ Two metrics of a film's suitability for this and other applications include (1) the availability of amine groups for crosslinking and (2) the zeta potential of the film, an indication of surface charge that affects the electrostatic interaction between proteins and a surface.^{24,25}

To confirm the amine functionality of the surface, coated and uncoated silica powder were exposed to fluorescein isothiocyanate (FITC), which is expected to react with surface amines and can be detected with a western blot imager. After exposure to FITC, the amine-coated silica is seen to fluoresce under 532nm light, as denoted by the green color, while the FITC-treated uncoated silica does not (Figure 5a). This indicates that the MLD-grown polyurea can serve to functionalize silicon dioxide such that it contains amine functional groups capable of reacting with the isothiocyanate crosslinking chemistry.

The zeta potential of polyurea coated silica powder was also analyzed between pH 5-10 and compared to uncoated silica, as seen in Figure 5a. Results of this measurement suggest that the isoelectric point lies somewhere below 5, at acidic pH. Interestingly, despite the surface amine functionality, very little change is seen in the film's acidity compared to the underlying silica, which is well characterized to have an isoelectric point (IEP) of about pH 2.0,²⁶ while the IEP of ethylamine is about pH 10.7.²⁷ Though surprising, some sparse research has observed the apparently minimal effect of a (basic) amine-terminated film on an (acidic) silicon surface.^{26,28,29} In spite of this, it is clear from the fluorophore crosslinking result that the surface has been modified from the original silica surface, apparently to an amine functionalized end. The impact of MLD on the zeta potential of silicon surfaces is of interest to many of its applications and is worthy of further research.

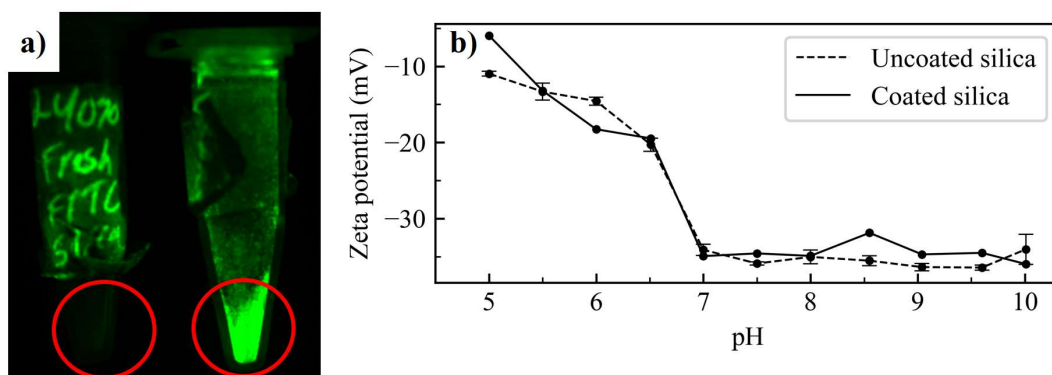


Figure 5) a) Coated (right) and uncoated (left) silica that has been exposed to fluorescein isothiocyanate. Note that the labels are fluorescing as well, and circles have been drawn on the silica. b) the zeta potential of coated vs uncoated silica. B

Methods

MLD deposition. 2,4-toluene diisocyanate and ethylene diamine were purchased from Sigma Aldrich and used without purification. Silicon wafers were purchased from University Wafers, cut into ~1x2cm rectangles, and treated with a Piranha etch (7:3 ratio of sulfuric acid to peroxide) before being placed into a custom-build hot-walled

ALD-style reaction chamber, which is pumped to <10mTorr of pressure. An MLD cycle consisted of: pre-dose pump down to base pressure, dose (ie open valve to precursor), hold/soak (chamber isolated from vacuum and precursor), purge (open vacuum and nitrogen lines for a crossflow of N₂), as described previously³⁰. The GPC for this process was determined by dosing TDIC/ED with [pump down, dose, hold, purge] times of [5,300,0,4,120] and [5,30,270,4,120] respectively. For the saturation curves, a combination of dose + hold is reported as the “dose” value. Powder depositions were performed on Davisil grade 643 silica gel purchased from Sigma Aldrich. To perform powder depositions in the reaction chamber, a small amount of powder was placed into a holder made of an NPT pipe nipple and cap with filter mesh and placed into the reactor chamber. Polyurea film depositions on powder used a recipe of TDIC/ED [4,150,1200,1200] / [4,15,1200,1200].

Ellipsometry. All thickness measurements were made with a Woolam Alpha SE Spectroscopic Ellipsometer at an angle of 70 degrees. The optical properties model includes a silicon substrate, native silicon dioxide layer (18Å) and Cauchy transparent film layer with optical constants A=1.600, B=0.014, C=0.000

FTIR. Polyurea coated silica powder was mixed with FTIR grade KBr purchased from Sigma Aldrich, ground in a mortar and pestle, and pressed to 2.5 tons using a pellet press. This pellet was analyzed on a Thermo-Nicolet iS10 FT-IR in the transmission geometry using an un-purged DGTS detector with un-coated silica powder as a blank.

XPS. Silicon wafers with 50 cycles of TDIC/ED [5,300,0,4,120]/ [5,30,270,4,120] were analyzed on a Kratos Axis Ultra DLD X-ray Photoelectron Spectrometer

FITC Labeling. Coated and uncoated silica was immersed in 1mg/mL FITC in anhydrous ethanol in a nitrogen atmosphere for 72 hours, then rinsed with copious ethanol and deionized water on a 10um filter over a vacuum pumped fritted filter. The FITC treated silica was imaged on an Azure Biosystems Azure 600 Western Blot Imager using a 532nm source.

Zeta potential measurements. A series of 0.2M sodium phosphate buffers were prepared from phosphoric acid and sodium hydroxide in a single batch with continuous monitoring with an Oakton pH 450 meter and an Oakton model WD-35811-71 electrode. 1mg/mL of silica was suspended in a buffer solution, introduced to an omega cuvette, and sonicated prior to zeta potential measurement in an Anton Paar Litesizer DLS 500 in triplicate. 0.1M sodium hydroxide and copious DI water was used to clean the cuvette of residual silica particles before switching from uncoated to coated silica measurement series.

Conclusions

This work has presented the characterization of the TDIC/ED MLD system, which compared favorably to the common PDIC/ED system. The growth characteristics (GPC, saturation) are similar enough to that of PDIC/ED that TDIC could be easily substituted in any existing process. Ultimately, the ease of use of TDIC arises from its low melting point, a result of the symmetry-breaking positioning of the methyl and isocyanate groups, greatly increasing its vapor pressure at low temperatures compared to the solid PDIC. Additional work is needed to determine what impact this methylation and decreased (nonlinear) bond angle has on the material characteristics of the film, such as temperature resistance, ion permeability, density, and tensile properties.

We further demonstrated the potential for MLD to be used in protein immobilization by successfully crosslinking of a fluorescent label to coated silica, though the zeta potential of the film is apparently in conflict with the predominant concepts of surface charge arising from surface groups. Indeed, this appears to be a yet-unexplained difference between organic MLD films and inorganic ALD films, which show a wide range of zeta potential curves and isoelectric points depending on the nature of the film.³¹

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