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Inert Gas Enhanced Laser-Assisted Purification of Platinum Electron-Beam-Induced Deposits

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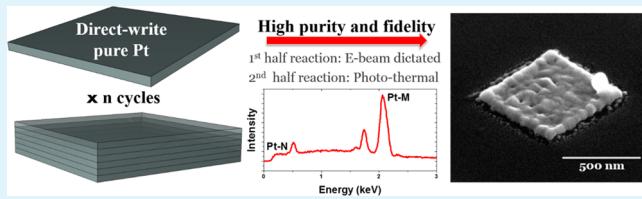
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Supporting Information

ABSTRACT: Electron-beam-induced deposition patterns, with composition of PtC_x, were purified using a pulsed laser-induced purification reaction to erode the amorphous carbon matrix and form pure platinum deposits. Enhanced mobility of residual H₂O molecules via a localized injection of inert Ar–H₂ (4%) is attributed to be the reactive gas species for purification of the deposits. Surface purification of deposits was realized at laser exposure times as low as 0.1 s. The ex situ purification reaction in the deposit interior was shown to be rate-limited by reactive gas diffusion into the deposit, and deposit contraction associated with the purification process caused some loss of shape retention. To circumvent the intrinsic flaws of the ex situ anneal process, in situ deposition and purification techniques were explored that resemble a direct write atomic layer deposition (ALD) process. First, we explored a laser-assisted electron-beam-induced deposition (LAEBID) process augmented with reactive gas that resulted in a 75% carbon reduction compared to standard EBID. A sequential deposition plus purification process was also developed and resulted in deposition of pure platinum deposits with high fidelity and shape retention.

KEYWORDS: *electron-beam-induced deposition, purification, atomic layer deposition, direct write, platinum*



INTRODUCTION

Focused electron-beam-induced processing (FEBIP) is capable of directly depositing and etching material with nanoscale resolution.^{1–3} Electron-beam-induced deposition (EBID) occurs when a precursor species is decomposed by a focused electron beam, resulting in a condensed deposit and some volatile reaction byproducts. This technique enables three-dimensional direct write of nanoscale structures via an intelligent control of the focused electron-beam raster sequence. An improved understanding of the fundamental electron-precursor-solid interactions have led to advances in growth rate and resolution of the EBID process.^{4–7} These advancements have enabled the emergence of many applications for materials grown via the EBID technique such as direct write plasmonic structures,^{8,9} field-emission emitters,^{10,11} maskless lithography,^{12–15} lithography mask editing,^{16–19} scanning probe tips,^{20,21} superconducting nanostructures,^{22,23} electrical contacts,²⁴ and nanomagnetic logic,^{25,26} to list a few.

Although EBID has been used for the aforementioned applications, a major liability has been the inclusion of unwanted byproducts in the final deposit. Because EBID is typically carried out at room temperature using standard chemical vapor deposition precursors, the precursor ligands do not completely volatilize via electron stimulated reactions. This results in the inclusion of unwanted ligands and ligand fragments in the deposit.²⁷ In the case of the commonly used organometallic trimethyl(methylcyclopentadienyl)-platinum(IV) (MeCpPt^{IV}Me₃), incomplete volatilization during the

EBID process results in the inclusion of methyl ligands and other carbon rich byproducts. Hence the final deposit is a PtC_x material with $5 \leq x \leq 8$,^{28,29} that consist of platinum nanoparticles embedded within a hydrogenated amorphous carbon matrix. Many purification techniques have been explored to address the EBID contamination issue with varying success.¹ Some of these approaches include post- and in situ electron irradiation,^{30–35} use of more easily volatilized precursors,^{36–38} postdeposition annealing,^{39–41} reactive gas coflow,^{42–44} and in situ substrate heating,^{39,45} to name a few. Martin et al. have recently demonstrated that inert gas flow can enhance electron-beam-induced etch rates of carbon, by increasing the flow of residual chamber reactive gases.⁴⁶

Recently, we have demonstrated enhanced purification of EBID deposits using an in situ laser anneal technique. In this process, so-called laser-assisted electron-beam-induced deposition (LAEBID), synchronized laser pulses were used to assist intermittently in the thermal desorption of byproducts after each electron-beam pass.⁴⁷ This method was successful in improving deposit purity as well as spatial resolution of the direct write EBID process; however, LAEBID could not completely purify the deposits. To promote further purification of EBID patterns deposited from the MeCpPtMe₃ organometallic precursor, we recently demonstrated an in-chamber

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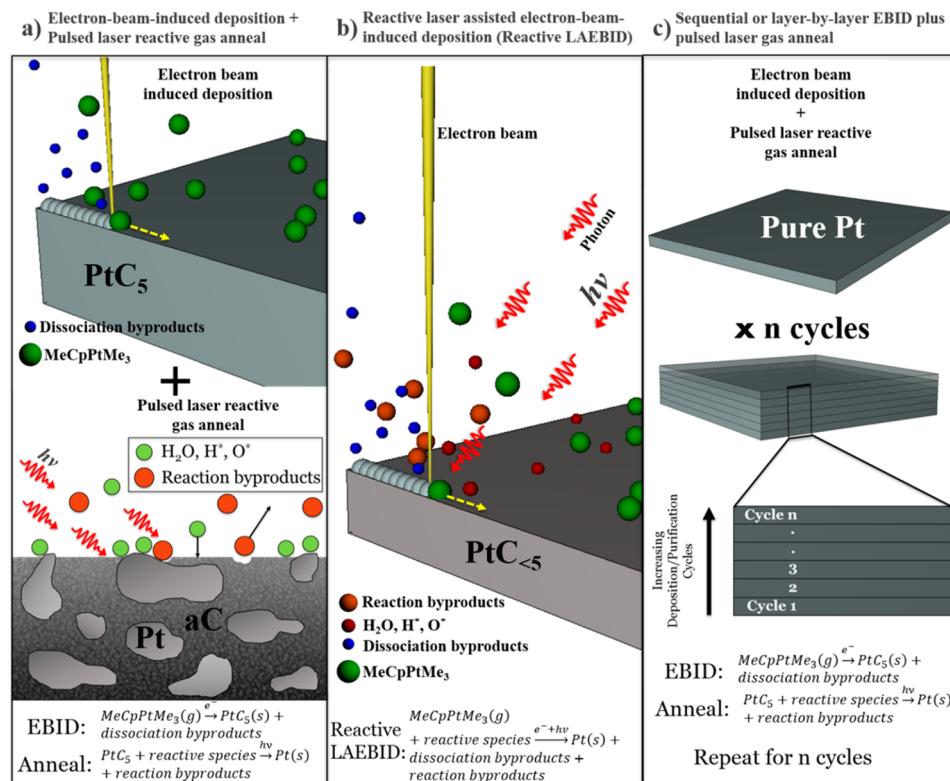


Figure 1. Schematic of the (a) EBID + pulsed laser reactive gas anneal, (b) reactive laser-assisted electron-beam-induced deposition, and (c) sequential or layer-by-layer EBID plus laser reactive gas anneal purification processes.

pulsed laser-induced oxidation purification process.⁴⁸ The process was able to fully purify deposits in a minimally invasive manner via a photothermal oxidation reaction. Adversely, a 70% volumetric reduction upon removal of carbonaceous byproducts resulted in a loss in precise shape retention and fidelity of deposits.

To increase purity, shape retention, and fidelity of EBID deposits, here we have developed a laser-induced purification reaction using residual H₂O molecules as a reactive gas species whose mobility to the EBID reaction zone is enhanced by a localized flow of Ar or Ar–H₂ (4%). Furthermore, we explored *in situ* strategies to deposit pure patterns that have cyclic deposition and purification steps. Specifically, we use an infrared pulsed laser delivery system mounted on a high angle port of a dual-beam system to irradiate EBID deposits under a localized ambient of inert Ar–H₂ (4%) or Ar gas. While initially we attributed the purification process to be due to a localized hydrogenation from the localized 4% H₂, subsequent experiments demonstrated that a pure Ar flow also results in purification. Thus, as described below, the enhanced reaction is attributed to enhanced surface diffusion of residual H₂O molecules to the EBID deposit via the localized Ar gas injection. The deposits are photothermally heated and facilitate the dissociation of the H₂O molecules into O^{*}, H^{*}, and OH^{*} radicals and the radicals subsequently react with the carbonaceous matrix in the PtC_x to form volatile byproducts. Hence, hydrogenation and oxidation reactions are attributed with the removal of the carbonaceous matrix. We also demonstrate an *in situ* reactive gas-assisted LAEBID process as well as a sequential deposition and purification technique. The later succeeds in depositing pure patterns with high shape retention and resembles a direct write ALD process with a first half-reaction driven by electron-beam-induced deposition and the second

half-reaction driven by the photothermal hydrogenation reaction with the carbon byproducts. In this work, the terminology “ALD” is not used to reflect that an exact monolayer of material is deposited per cycle. Rather, “ALD” is used in the sense described by Kanarik et al.,⁴⁹ which states that the process benefits from separate self-limiting half-reactions with atomic-scale fidelity. Schematics illustrating the purification techniques studied here are shown in Figure 1.

EXPERIMENTAL SECTION

Electron-Beam-Induced Deposition. EBID was performed using an FEI Nova Nanolab 600 Dual Beam system on a Si substrate with a 200 nm thick thermally grown silicon oxide layer. The chamber was air plasma cleaned with an Evactron system, produced by XEI Scientific Inc., for a minimum of 15 min prior to deposition. Unless noted, EBID was carried out by locally injecting MeCpPtMe₃ precursor in close proximity to the area of interest where the GIS needle was positioned ~100 μm above the substrate and ~200 μm from the center of the field of view. The MeCpPtMe₃ crucible was heated to approximately 45 °C to increase the vapor pressure of the precursor. The chamber pressure was ~1.0 × 10⁻⁵ mbar during injection of the MeCpPtMe₃ precursor into the chamber with a base pressure of ~1.0 × 10⁻⁶ mbar. Each pattern was deposited using 5 keV electron-beam energy, 98 pA beam current, 10 μs dwell time, and a 13.6 nm pixel pitch. The number of EBID passes were varied (1000, 2000, 4000, and 8000) to create deposits that were approximately 25, 50, 90, and 240 nm thick.

Pulsed Laser Reactive Gas anneal. A 915 nm wavelength 25 W multichip diode laser module with model number BMU2SB-915-01, produced by Oclaro Inc., was used to anneal the deposits. This laser module was driven by an IXYS PCX-7410 pulsed diode laser driver. A laser delivery system, produced by Omniprobe, Inc. (an Oxford Company), was mounted on a high angle port in the SEM chamber at an angle of 52° relative to the substrate. This system enabled the simultaneous delivery of an approximately 100 μm diameter laser spot size with a Gaussian distribution to the EBID deposit in the SEM

chamber. Inert Ar gas was delivered to the area of interest using an OmniGIS I gas injection system; the inert gas contained a small mixture of H₂ gas (4 vol %). Subsequent comparisons with pure Ar gas, reveal that the H₂ species have no observable contribution toward the purification process. The needle was positioned ~100 μm above the sample and ~200 μm from the center of field of view. The chamber base pressure before reactive gas flow was ~1.0 × 10⁻⁶ mbar. The valve pulsing rates in the OmniGIS I, which ultimately control the reactive gas flux, were set to achieve a chamber pressure of 1.2 × 10⁻⁵ mbar when the reactive gas was flowing, and the gas temperature was 25 °C. The needle configuration for deposition and the subsequent purification are illustrated in Figure 2. For this work, the optical power

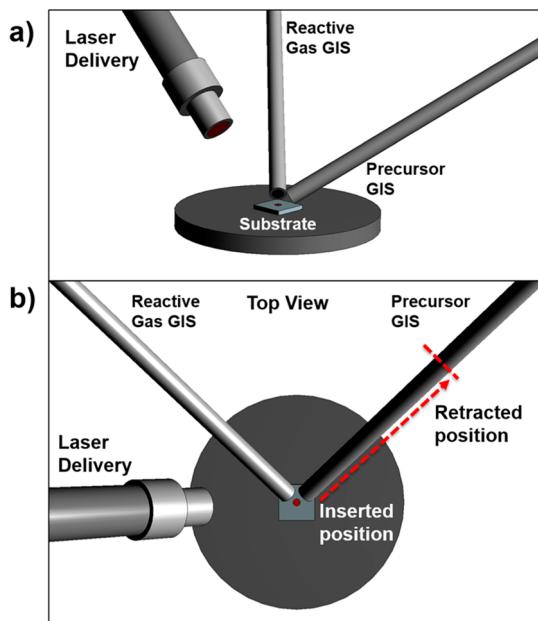


Figure 2. Schematic of deposition and annealing experimental setup from (a) tilted and (b) plane view. The laser delivery system, focused electron beam, precursor GIS, and reactive gas GIS converge to a single point. During reactive LAEBID processes, the precursor GIS needle is in the “retracted” position (dotted red line), which is withdrawn to ~8 cm vertically and ~5 cm horizontally from the point of interest to reduce precursor flux at the substrate. During the sequential deposition plus annealing process, the needles are configured in the as-shown inserted states.

density of the laser was constant at ~165 kW/cm². Laser pulse width and duty cycle were varied with the laser driver. Additional information on the laser delivery system can be found in reference.⁵⁰ The EBID and subsequent pulsed laser reactive gas anneal processes are illustrated in Figure 1a.

Reactive Laser Assisted Electron-Beam-Induced Deposition.

Reactive laser-assisted electron-beam-induced deposition (LAEBID) was carried out by performing EBID to deposit PtC_x patterns while simultaneously irradiating the EBID deposit with the pulsed laser in a Ar inert gas coflow, where the Ar once again increases flux of the reactive gas (H₂O) to the deposit region. EBID was conducted using 5 keV electron-beam energy, 98 pA beam current, 10 μs dwell time, and a 13.6 nm pixel pitch. A schematic of this process is illustrated in Figure 1b. Some LAEBID deposits included an additional 13.6 ms refresh time after each EBID pass to lengthen reactive gas annealing time per pass. During the EBID pass, the laser was simultaneously pulsed with either 10 or 100 μs pulselwidths. The irradiation duty cycle was varied over the range of 0.1%–6% (see the Supporting Information for more details and Figure S1 therein, which shows a schematic illustrating a map of laser and EBID synchronization). For this work, the FEI GIS for the MeCpPtMe₃ precursor gas as well as the OmniGIS I for the inert gas were opened concurrently to establish the

coflow regime. The partial pressures of the Ar inert gas and MeCpPtMe₃ precursor introduced into the chamber were approximately 1.10 × 10⁻⁵ mbar and 9.0 × 10⁻⁶ mbar, respectively. During the coflow experiments, the precursor gas nozzle was retracted ~8 cm vertically and ~5 cm horizontally while the reactive gas GIS needle was positioned 100 μm above the sample and 200 μm from the center of field of view (see Figure 2). By comparison, in the typical EBID experiment the precursor gas nozzle is located in the same close position. Ultimately, this needle configuration significantly decreases the flux of MeCpPtMe₃ precursor gas molecules relative to the reactive gas molecules to slow the EBID growth and enhance the purification of the deposits.

Sequential or Layer-by-Layer EBID Plus Laser Reactive Gas Anneal.

As will be demonstrated, the co-flow of gases used in the LAEBID process, prohibit complete volatilization of unwanted byproducts in the final deposit. To circumvent the issues of the co-flow of precursor gas and reactive gas in the LAEBID process, a sequential deposition and purification process was also developed. In this process, precursor gas and Ar inert gas were injected (separately) into the chamber under standard EBID and laser annealing parameters. A 30 keV beam energy and 150 pA beam current were used for deposition in this study to minimize peripheral PtC_x deposition on the substrate.^{51,52} For the layer-by-layer process, an optimum EBID thickness per cycle was determined to be 70 nm (see the Supporting Information Figure S4). After the EBID cycle, the precursor gas was pumped from the chamber until a base pressure of ~2.0 × 10⁻⁶ mbar was achieved and Ar inert gas was injected into the chamber to enhance flow rate of residual H₂O to the deposit at a pressure of ~1.2 × 10⁻⁵ mbar. The pulsed laser system was then used to irradiate the sample with 10 μs pulses at 1% duty cycle for a total laser exposure time of 3.0 s and equivalent process time of 5 min. After each cycle, the deposit was irradiated with several 100 μs laser pulses to initiate the coalescence of any disconnected Pt grains in the deposit. This step was required to mitigate the evolution of porosity in the final morphology. For the sequential approach, the needles for the reactive gas and precursor gas were both positioned 100 μm above the sample and 200 μm from the center of field of view (as shown in Figure 2). The sequential EBID + laser anneal process was repeated in order to create a pure deposit of desired size and shape and a schematic of this process is shown in Figure 1c.

Energy Dispersive Spectroscopy (EDS) Analysis. EDS spectra were recorded while irradiating the substrate with a 5 keV energy electron beam at a beam current of 1.6 nA. Analysis to determine the normalized carbon content of each spectra was conducted by first subtracting a background spectra of the underlying SiO₂ substrate. The Pt and C EDS signatures, located at 2.048 and 0.277 keV respectively, were then fit with a Gaussian curve of the form shown in eq 1:

$$y = y_0 + \frac{Ae^{-4\ln(2)(x-x_c)^2/w^2}}{w\sqrt{\frac{\pi}{4\ln(2)}}} \quad (1)$$

where x_c is the center of the EDS peak, A is the amplitude, and w is the full-width at half-maximum. The area under the curve was taken to be a measure of the elemental concentration of the deposit. Because of variability in EDS yield of the different elements, we solely report the carbon content normalized to a standard EBID deposit's carbon content to give an indication of the deposit purity. It is well-known that the Pt-N and C-K EDS peaks overlap. The Pt-N/Pt-M peak ratio was experimentally determined to be approximately 0.03 for our EDS system. This is notably lower than the Pt-N/Pt-M determined by other work to be 0.09, and is likely attributed to a difference in sensitivity of the lower energy portion for the detector. This proportionality constant was used to determine contribution of the Pt-N peak from the Pt-M peak located at 2.048 keV. The estimated contribution of the Pt-N peak was then subtracted from the EDS peak located at 0.277 keV to produce a more accurate estimate of the actual carbon EDS peak.

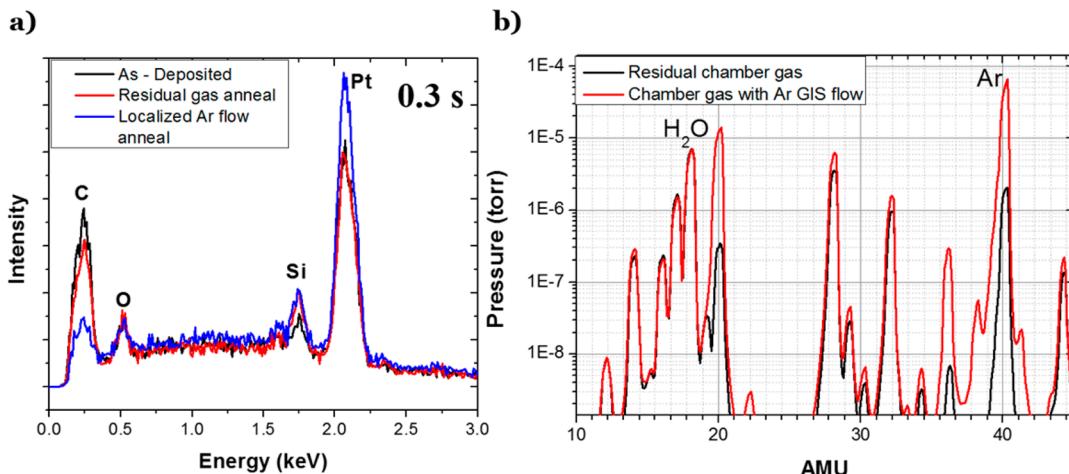


Figure 3. (a) EDS spectra of Pt EBID deposits that were annealed with 10 μ s and 1% duty cycle laser conditions for a cumulative laser exposure time of 0.3 s. Spectra shown include an as-deposited pattern, a deposit anneal under chamber ambience, and a deposit annealed under localized Ar gas flow. (b) RGA spectra showing the residual chamber gas species present as well as during Ar flow.

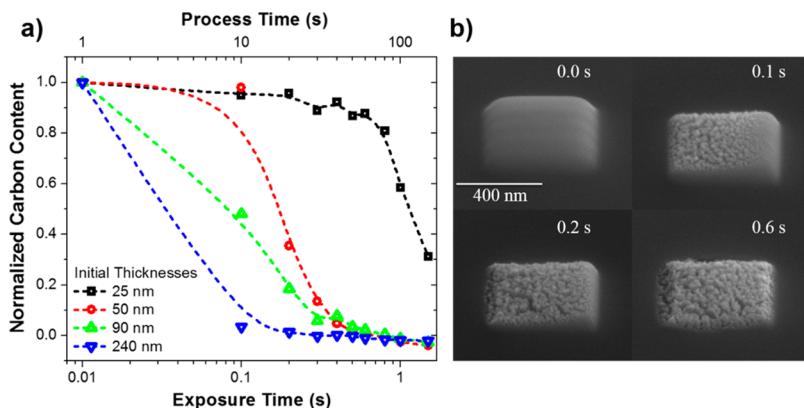


Figure 4. (a) Carbon content, from EDS measurements, as a function of laser exposure time (duty cycle \times processing time, bottom axis) and processing time (top axis) for 10 μ s at 1% laser duty cycle. The deposit thicknesses were approximately 240 nm, 90 nm, 50 nm, 25 nm, which correspond to 8000, 4000, 2000, and 1000 passes, respectively. Normalized carbon content of 1, is that of a standard PtC₅ EBID deposit. (b) SEM images of an annealed deposit that was initially \sim 90 nm as-deposited. Inset time reflects the total laser exposure time for each anneal.

RESULTS AND DISCUSSION

Figure 3 displays the EDS spectra of EBID PtC₅ deposits that were irradiated with the 165 W/cm² optical power density, 10 μ s pulse width, and 1% duty cycle laser conditions for 0.3 s of laser exposure time. Two conditions are compared where the deposits were laser annealed (1) in the presence of residual chamber gases at a chamber base pressure of 5.2×10^{-6} mbar, in which H₂O is the dominant residual gas, and a (2) localized flow of inert Ar gas. Clearly, the deposit that was annealed under localized Ar ambient experienced greater reduction in carbon content. The localized Ar gas species is inert thus not suspected to contribute to the chemical etching of the carbonaceous matrix within the deposits, however inert gas flow has been shown to increase concentration of residual H₂O adsorbates in the area of localized flux.⁴⁶ Hence, the purification mechanism envisioned is a multistep process where (1) Ar gas is locally injected by a GIS, (2) the localized Ar bombards substrate surfaces and enhances the H₂O diffusion rate, (3) H₂O diffuses onto the EBID deposit, and (4) thermal energy supplied by the laser facilitates the dissociation of H₂O into radicals that react with the carbon matrix in PtC₅ deposits and forms volatile compounds that subsequently desorb.

Residual H₂O that contributes toward the thermally driven purification reaction have multiple possible origins from within the system. Specifically H₂O molecules may be supplied from (1) outgassing of chamber walls, (2) outgassing of the substrate, or (3) from contamination in the inert gas line. Figure 3b compares residual gas analysis (RGA) taken of residual chamber gases and during localized Ar flow. Minimal differences in the chamber partial pressure of H₂O (18 amu) molecules with and without localized Ar (20 and 40 amu) flow suggests that the H₂O species that contribute toward the purification process are not delivered from the inert gas line. Inert gas flow localized to the substrate as well as nonlocalized flow should have similar effect at facilitating H₂O outgassing at the chamber walls. Additional laser anneals of PtC₅ deposits with nonlocalized Ar flow shows minimal purification (see the Supporting Information), and thus rules out enhanced contribution from H₂O from the chamber wall. Hence, we conclude that the localized Ar gas flux supplied from the GIS needle facilitates the localized enhanced surface diffusion of H₂O from the substrate, which is the dominant contributor toward the purification reaction.

Figure 4 illustrates the integrated normalized carbon EDS peak for various PtC₅ deposit thicknesses as a function of laser

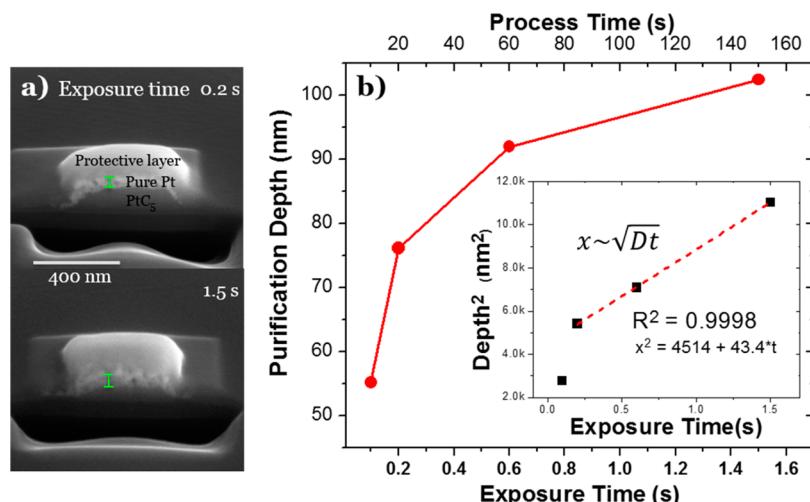
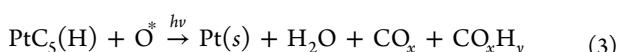


Figure 5. (a) SEM cross section images of deposits annealed with reactive gas for 0.2 and 1.5 s of total laser exposure time. (b) Purification thickness from an originally ~ 240 nm thick PtC₅ deposit as a function of pulsed laser exposure time for a $10\ \mu\text{s}$, 1% duty cycle anneal while under Ar gas flow. The inset shows the plot and linear regression of purification thickness squared versus time, which is consistent with a diffusion limited purification regime.

exposure (and process) time. The deposits were irradiated with $165\ \text{W/cm}^2$ optical power density, $10\ \mu\text{s}$ pulse width, and 1% duty cycle laser conditions in the localized Ar ambient. The PtC₅ EBID deposits used in this study had a $500 \times 500\ \text{nm}^2$ area with variable deposit thickness ($\sim 25, 50, 90$, and 240 nm by varying the number of EBID passes). As shown previously,⁴⁸ laser annealing with no localized gas flow does not eliminate the carbon. We also demonstrated, for O₂-laser annealing, that the PtC₅ deposit purification as a function of total laser exposure time (duty cycle \times process time) is highly dependent on the initial deposit thickness; thicker deposits anneal faster due to enhanced optical coupling of the laser to the PtC₅ (see the supplemental information of ref 48 for a detailed explanation of the role of these material parameters on the laser purification process). A similar behavior is demonstrated here, where the thicker deposits anneal at a faster rate due to enhanced photothermal heating of the deposit.

The purification evolution as a function of depth into EBID deposits were examined in Figure 5. Specifically, 240 nm thick PtC₅ deposits were irradiated with the $10\ \mu\text{s}$, 1% duty cycle pulsed-laser under flux from Ar inert gas. Deposit cross sections are shown for 0.2 and 1.5 s laser exposure times. For these exposure times, the purification front progresses into the deposit, but does not anneal the entire deposit. The proposed purification reactions upon the formation of radicals from H₂O dissociation are as follows



for the eq 2 hydrogenation and 3 oxidation purification reactions, respectively, where PtC₅(H) denotes the hydrogenated PtC₅ deposits. It is worth noting that a self-hydrogenation coreaction may also play a role during purification due to residual hydrogen present in the amorphous carbon from the original EBID process. Under laser-irradiation and applied heat, dehydrogenation of some ligands result in the hydrogenation and hence volatilization of other ligands producing CH_x or CO_xH_y byproducts,⁵³ thus possibly contributing a secondary role in the purification. Dehydrogen-

ation of the amorphous carbon matrix can also result in the formation of additional water molecules under oxygen flux, which may also be tertiary reactions contributing toward the overall purification reaction.³¹

Figure 5b is a plot of the purified platinum thickness as a function of laser exposure time for the pulsed laser purifications. To sustain the top-down subsurface purification reaction, the transport of the reactive gas to the reaction front is envisioned to occur via a two-step process, namely (1) the reactive gas radicals adsorbs onto the purified Pt surface after thermal dissociation of H₂O molecules and (2) subsequently diffuses to the purification front through the nanoscale porosity that develops. There is also likely purification contribution from H₂O molecules that adsorb and diffuse into the deposit prior to dissociation. Because Pt serves as a catalyst for many hydrogenation and oxidation reactions,^{54,55} these species will readily chemisorb onto the deposit surface. Therefore, as the Pt surface layer thickens, diffusion of the reactive species to the purification front is expected to be the rate limiting transport mechanism. Recently, purification simulations interrogating the PtC₅/O₂ interaction have revealed that transport is dictated by the cyclic process of dissociation chemisorption/associative desorption on Pt surfaces coupled with O₂ diffusion between Pt interactions.⁵⁶ This combined process can be described using an effective diffusion coefficient that is typically much smaller than the diffusion of the gas alone. We suspect that the coupled diffusion process is similar for both reactive gas radicals active here, O and H. The inset plot in Figure 5b plots the purification depth squared as a function of laser exposure time. Because the diffusion depth of the reactive gas species into a material has a \sqrt{Dt} dependence, the linearity ($R^2 = 0.9998$) of the plot is consistent with a diffusion limited purification rate. Hence the diffusion limited purification rate reveals the need for in situ deposition and purification processes for thick deposits because the time required for diffusion of reactive gas species into the interior of the deposit follows a squared dependency with the depth.

Roberts et al. developed a pulsed-laser-assisted process for in situ purification of EBID deposits, namely laser-assisted electron-beam-induced deposition (LAEBID).^{47,57} In this

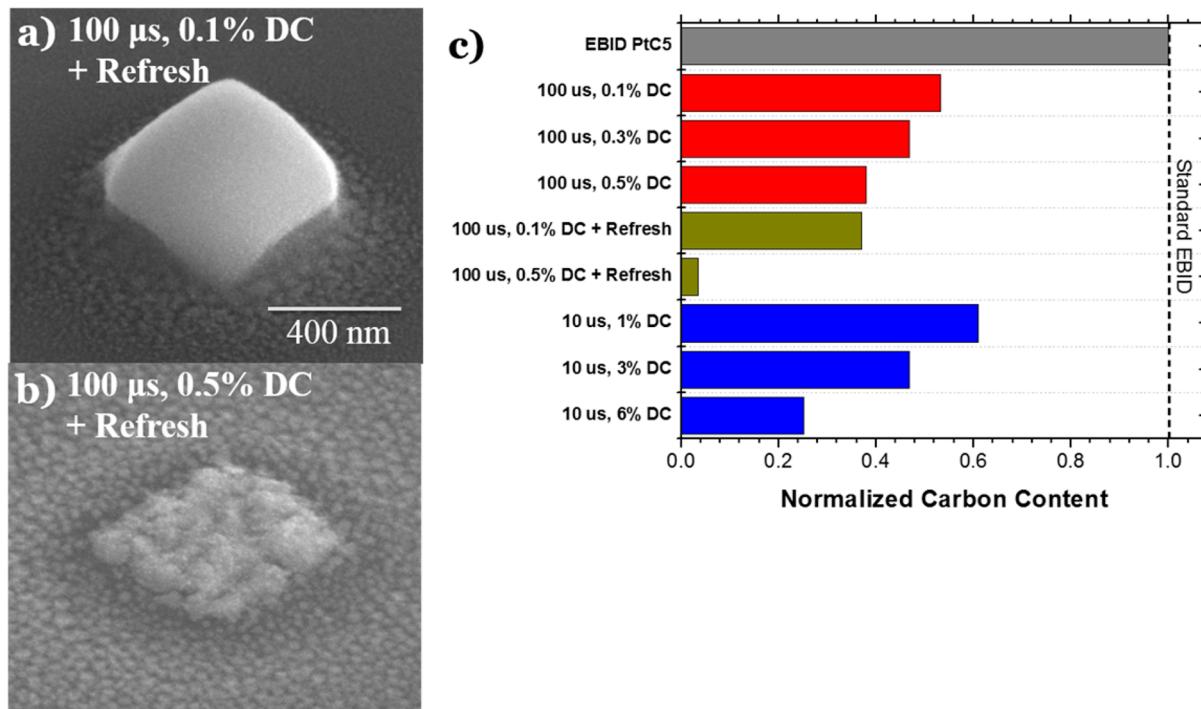


Figure 6. (a) SEM tilt image of a typical laser-assisted electron-beam-induced deposition (LAEBID) pattern deposited with coflow of reactive gas. Specifically, this deposit was created 100 μ s and 0.1% duty cycle laser conditions. The electron beam and gas conditions were as listed in the experimental details. (b) SEM image of a LAEBID pattern deposited with 100 μ s and 0.5% duty cycle laser conditions, which shows contribution from LCVD. The deposit retains shape with high fidelity. (c) Comparison of LAEBID patterns deposited with various laser and refresh parameters. Refresh denotes extra time between LAEBID passes to enhance the laser-on time relative to the EBID time. Additional process parameter information may be found in the Supporting Information.

work, laser pulses were synchronized with EBID passes and the highest purity (~37 at. % Pt) was achieved when the EBID layer thickness per laser pulse was approximately a monolayer of deposited material. Importantly, the deposits were grown on a titanium film that facilitates the optical coupling and subsequent heating necessary for the thermally driven purification. Nonetheless, even with a monolayer-by-monolayer purification approach, carbon content remained in the deposits (optimum purification realized \sim PtC₂). To try promoting further purification, here we introduce a reactive gas to the LAEBID process. We envision the reactive gas-assisted LAEBID process as a direct-write atomic layer deposition (ALD) process with an electron-beam dictated first half-reaction followed by a reactive gas purification second half-reaction dictated by laser heating. Ar inert gas was injected simultaneous with the precursor gas to provide a coflow (using two individual injection systems) of species necessary for deposition and purification, where once again, the Ar species increases the localized diffusion of H₂O reactive to the deposit. Notably, subsequent studies revealed that precise synchronization and laser pulsing during the refresh time of the EBID layer is not necessary because the electron beam is only irradiating a single pixel while the laser pulse irradiates the entire deposit. This effectively gives refresh time for the other pixels, which have no interaction with the electron beam at that moment in time. Thus, the results presented here were not synchronized with the refresh time.

Figure 6a shows an SEM image of a deposit following reactive LAEBID (100 μ s pulse width and 0.1% duty cycle). The deposit demonstrates exceptional shape retention and smoothness. In addition, a decrease in carbon content relative to

standard PtC₅ EBID resulted (Figure 6b). A variety of laser conditions were explored for the reactive LAEBID process in an attempt to promote further purification of the deposits. Changing the duty cycle from 0.1% to 0.5% for 100 μ s pulse width (red bars) resulted in a decrease in carbon content from 53% (relative to standard EBID) to 38% by providing a greater laser exposure time during deposition. To increase the laser exposure time relative to the EBID half-reaction, an additional 13 ms refresh time after each pass of deposition (yellow bars) was added to purify further the deposits. During the refresh time, the electron beam was blanked and only the laser anneal half-reaction occurs. The added refresh time resulted in a further reduction of carbon. However, the increase in cumulative laser exposure also resulted in laser-assisted chemical vapor deposition (LCVD) in the laser irradiation area (\sim 100 μ m) as shown in Figure 6b. Therefore, the deposit thickness evolves from a convolution of LAEBID and LCVD processes and results in a loss of deposit shape retention. Additional information on the competing LCVD phenomenon is detailed in the Supporting Information.

The reactive LAEBID process was also attempted with a pulse width of 10 μ s and a variable duty cycle of 1, 3, and 6% (blue bars). The 10 μ s pulse width yields a lower maximum deposit temperature (~490 K) relative to the 100 μ s pulse width (~600 K) due to the nonsteady state behavior of the laser heating.⁴⁸ Higher duty cycles can be tolerated at 10 μ s, relative to 100 μ s, because less time is required for recovery to room temperature between pulses. Thermal pulse interactions are intentionally avoided in order to both simplify the interpretation of results and avoid a steady state temperature

transient over the process time that can favor both LCVD and thermal drift.

Increasing the duty cycle of the $10\ \mu\text{s}$ pulses to 6% resulted in a reduction in the carbon content of the deposit from 60% to 25% relative to standard EBID, which represents the highest purity obtained in our Pt LAEBID deposits that excludes LCVD effects. Beyond 6% duty cycle resulted in steady state heating and thermal drift during the LAEBID process. Summarily, reactive LAEBID realized a reduction in carbon content of 75% relative to standard EBID; however, complete carbon removal was not achieved. The challenges preventing complete purification are addressed below.

To understand the effect that the MeCpPtMe₃ precursor gas had on the photothermal half-reaction in the LAEBID process, standard EBID PtC₅ patterns were grown and subsequent laser anneals were carried out with (1) the Ar inert gas flow alone, and (2) a coflow of Ar reactive gas and MeCpPtMe₃ precursor where the precursor nozzle was positioned at approximately 7 mm from the center of field of view and 5 mm above the substrate, sufficient to decrease significantly the MeCpPtMe₃ flux as evidenced by a significant decrease in the EBID growth rate at this position. Figure 7 is a plot of the normalized carbon

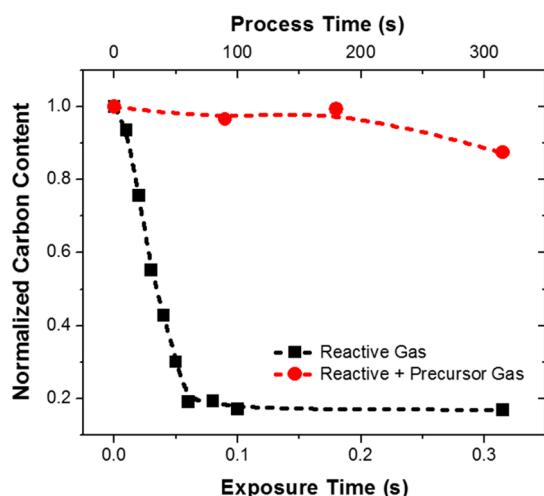


Figure 7. Normalized carbon content for standard EBID deposits annealed in reactive gas only (black) and a coflow with approximately equal localized pressure of reactive gas plus the organometallic MeCpPtMe₃ precursor (red). Deposits were annealed with $100\ \mu\text{s}$, 0.1% laser duty cycle conditions.

content of the laser annealed deposits as a function of laser exposure time irradiated with $100\ \mu\text{s}$ pulse width and 0.1% duty cycle pulses. Clearly, when annealed with the Ar flow alone, the purification rate is fast relative to the sample laser annealed with the precursor gas coflow. It is therefore deduced that the presence of the precursor molecule attenuates the purification reaction, thus making complete carbon removal in the reactive gas-assisted LAEBID process challenging.

The schematics shown in Figure 8 illustrate a proposed mechanism for the laser-annealing attenuation exhibited when a coflow of reactive gas/precursor molecules is used. Figure 8a illustrates the common microstructure of PtC₅ deposits, namely platinum nanograins are embedded within an amorphous carbon matrix. In the presence of the Ar gas flux, residual H₂O molecules adsorbed to the substrate exhibit enhanced diffusion rates that reduce the reactive gas replenishment time. Radicals created upon dissociation of H₂O molecules, then react with

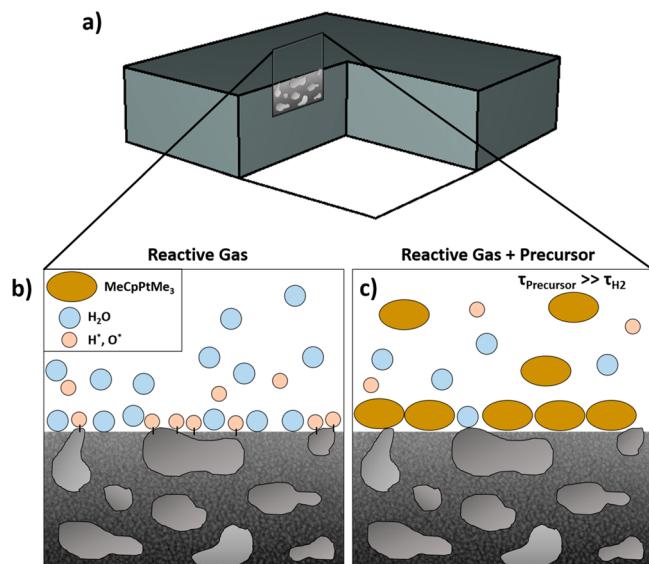


Figure 8. Schematic of proposed purification retardation mechanism. (a) EBID PtC₅ deposit is composed of Pt nanoparticles suspended within an amorphous carbon matrix. (b) Under a flux of molecular H₂O only, there are many adsorption sites for the purification reaction to occur. (c) With a coflow of H₂O and MeCpPtMe₃, the MeCpPtMe₃ precursor gas dominates the surface coverage due to the long residence time and occupies many adsorption sites and reduces purification rate.

the carbonaceous matrix through hydrogenation and oxidation reactions to reduce embedded carbon content. When a reactive and precursor gas coflow is used (Figure 8c), the relative residence times of the gas molecules on a surface must be considered to realize the resultant equilibrium surface coverage. Large molecules, such as the MeCpPtMe₃ precursor used in this study, have longer residence times on the deposit surface than the dissociation H* and O* radicals. As the schematic illustrates, the precursor molecules dominate the surface coverage on the deposit surface due to their long residence time (τ). This effectively lowers the coverage of the reactive gas by reducing available adsorption sites and attenuates the purification reaction. Understanding that the coflow of precursor gas in the presence of reactive gas species attenuates the purification reaction helps explain why the complete LAEBID reaction is limited under laser conditions that would otherwise purify an EBID deposit. This suggests that a pulsed gas procedure is necessary for the in situ growth and purification of EBID deposits, similar to a true atomic layer deposition (ALD) process.

To circumvent the apparent gas competition issues with coflow, a pulsed gas procedure was utilized in a sequential EBID deposition and subsequent laser anneal process. Specifically, precursor gas was injected during the EBID half-reaction, which was subsequently pumped from the chamber. The precursor partial pressure introduced during this half-reaction was $\sim 9.0 \times 10^{-6}$ mbar. A 30 keV beam energy was used for EBID to prevent significant peripheral deposition, which is characteristic of a 5 keV beam with larger beam tails (see Supporting Information Figure S4). Next, the Ar inert gas was injected at a partial pressure of $\sim 1.2 \times 10^{-5}$ mbar during the photothermally induced decarburation second half-reaction to enhance diffusion of residual water molecules. Importantly, $10\ \mu\text{s}$ pulse width and 1% duty cycle laser condition were used to anneal the deposit during each cycle,

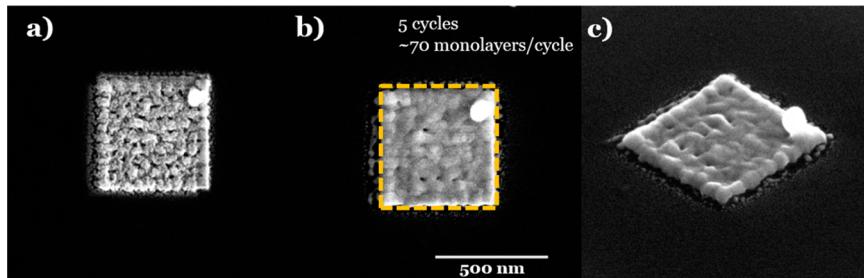


Figure 9. Sequential deposit fabricated from 5 cycles with approximately 70 monolayers deposited per cycle (a) before and (b) after 100 μ s smoothing pulses were applied to reduce porosity of the deposit. Inset dashed square denotes original pattern shape prescribed by EBID raster sequence. (c) SEM tilted image (52°) of the sequential deposit.

followed by several 100 μ s pulse width smoothing pulses. The 10 μ s pulses facilitate the decarburation of the deposit; however, the relatively brief pulses prevent significant coalescence of the Pt, thus promoting deposit shape retention. Several 100 μ s pulses are used to promote controlled coalescence after each purification cycle to reduce some deposit porosity while maintaining shape retention. This cycle was repeated to build a pure deposit of desired size and shape, as illustrated in Figure 1c. Unique to this process, compared to a traditional surface reaction limited ALD processes, the number of monolayers deposited per cycle is dictated by EBID half-reaction, which makes submonolayer resolution possible. The number of monolayers deposited per cycle largely effects the deposit characteristics as shown in the Supporting Information (Figure S4). Because of the ~70% volumetric loss during the decarburation reaction, significant internal stresses will be exhibited in the deposits if many (>200) monolayers are deposited per cycle. Large internal stresses may cause the deposit to delaminate from the substrate (Supporting Information Figure S4c), hence there is an optimum number of monolayers per cycle that will result in an acceptable deposition rate while preventing significant internal stresses from building up during the purification cycle. Figure 9a displays a pattern deposited using five cycles and ~70 monolayers of deposition per cycle before 100 μ s smoothing laser pulses were utilized to reduce porosity of the freshly deposited material from the cycle. Figure 9b displays the deposit after the smoothing pulses were applied. The yellow dotted line denotes the EBID raster pattern. Clearly, precise shape retention is achieved using this sequential deposition technique. Figure 9c is a tilted scanning electron image (52°) of the deposit, and the total thickness of the purified deposit is estimated to be ~50 nm (consistent with the ~70% volume reduction experienced when purifying a PtC₅ deposit). EDS spectra of sequential deposition patterns (Supporting Information Figure S4) reveal that the deposits are pure platinum. Hence the sequential deposition process can be utilized to direct write pure nanostructures.

The throughput of the layer-by-layer process seems noticeably lower than that of a single EBID deposition followed by a subsequent reactive gas anneal; however, the completeness of the anneal must be considered. Because the time for diffusion of a reactive gas species to deposit interior is proportional to the depth squared, it may be quite timely to anneal a single standard EBID deposit in its entirety and may result in the lack of shape retention. The throughput of the sequential layer-by-layer process also has a similar throughput to the completely in situ LAEBID process. This is because the deposition rate may be hindered in the LAEBID process because the elevated substrate temperature reduces gas residence time (for precursor

and reactive gas species). To comment briefly, the throughput of the sequential layer-by-layer process could be improved with a smaller deposition chamber, similarly to an ALD system. This would increase the pumping rates between cycles, enable a higher frequency cyclic process, and ultimately increase applicability of the process.

CONCLUSIONS

In conclusion, we have demonstrated a localized pulsed laser-induced purification reaction that can be used to purify PtC₅ EBID deposits generated via electron stimulated reactions of the MeCpPtMe₃ precursor. The reactive gas species was supplied by the thermal dissociation of residual H₂O molecules in the chamber, where inert Ar gas was used to enhance H₂O diffusion to the reaction zone. We have also demonstrated two direct write pseudoatomic layer deposition processes. Specifically, we have presented a reactive gas-assisted LAEBID process that is capable of depositing patterns from the MeCpPtMe₃ precursor with much greater purity than standard EBID, by utilizing intermittent 915 nm annealing laser pulses and residual H₂O molecules. We have also demonstrated a sequential deposition process to circumvent gas competition for adsorption sites that appears ubiquitous with the LAEBID process. The sequential deposition process utilized a pulsed gas strategy, similar to a traditional ALD process; however for this work, the first half-reaction was dictated by electron-beam irradiation and the second half-reaction was dictated via a photothermally induced purification reaction. The sequential deposition process was successful in deposition of pure nanostructures with high shape retention and fidelity.

As for our perspective on future development of this process, several parameters can surely be further optimized for higher efficiency and throughput. The 915 nm laser is largely transparent to oxide substrates as well as highly reflective on metallic substrates and deposits. Therefore, photothermal heating from this laser system is often inefficient. We speculate that lasers in the visible spectrum will heat the substrate or deposits with greater efficiency, thus increasing the throughput of the in situ and ex situ annealing strategies of EBID deposits. In the gas coflow LAEBID process, gas competition for adsorption sites between the reactive gas and precursor gas limits the deposit's purity. This suggests that flux of the reactive gas is not sufficient in comparison to the precursor gas to enable complete deposit purification. A similar setup in an environmental SEM enables the use of pressure regimes (not possible in a standard SEM), which may provide a gas mixture possible of facilitating complete purification in the LAEBID process.

ASSOCIATED CONTENT

Supporting Information

Synchronization maps for laser and electron beam for the laser-assisted electron-beam-induced deposition process, additional details for the LAEBID process, details about contribution of laser-assisted chemical vapor deposition, additional details about the sequential or layer-by-layer EBID process and images. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.5b02488.

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Notes

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