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US Army Research Laboratory

Hardware Modifications to the US Army Research Laboratory’s Metalorganic Chemical Vapor Deposition (MOCVD) System for Optimization of Complex Oxide Thin Film Fabrication

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NOTICES

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14. ABSTRACT

An introduction to various metalorganic chemical vapor deposition (MOCVD) reactor designs and precursor delivery methods for the growth of complex oxide thin films is presented with comments on the respective advantages and limitations of each variation. Hardware modifications were made to the US Army Research Laboratory’s MOCVD system in attempts to improve film purity and quality. A loading chamber was installed with a “wobblestick” load arm to protect samples from impurities in the main MOCVD chamber prior to deposition. Camera and light sources to provide a live video feed of the main MOCVD chamber were also installed to assist with the transportation of samples from the load chamber to the sample heater. Strontium titanate thin films were grown on platinized silicon substrates and were characterized by X-ray diffraction, scanning electron microscopy, and atomic force microscopy to investigate the impact of the implemented hardware modifications on composition, film quality, and homogeneity.

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Contents

List of Figures

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1. Introduction

1.1 Background

Metalorganic chemical vapor deposition (MOCVD) is a method of thin-film deposition that was originally developed in the late 1960s for the growth of epitaxial compound semiconductor films. MOCVD is a fabrication technique that falls within the umbrella of CVD techniques, which deposit a solid material on a substrate by means of a chemical reaction of volatile materials in vapor phase. CVD techniques contrast from physical vapor deposition (PVD) techniques mainly in that PVD involves physical reactions such as condensation or bombardment of material species instead of chemical reactions at the desired thin-film surface.[1] While there are many variations of CVD techniques, MOCVD focuses on the use of metalorganic precursor materials, which mainly consist of molecules with metallic species attached to organic ligands (Fig. 1).

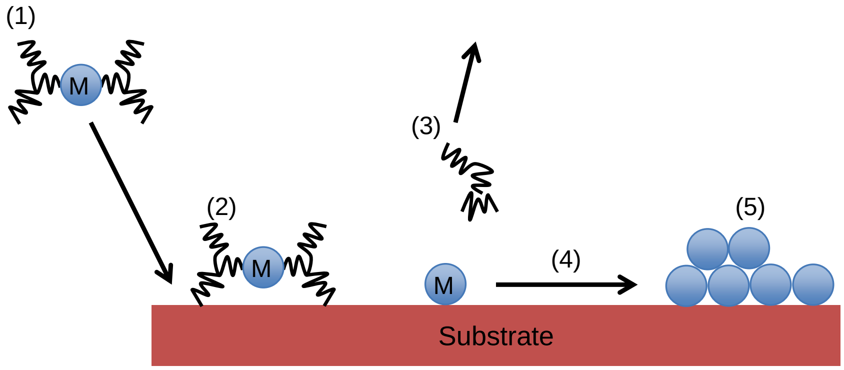


Fig. 1 Simplified schematic of MOCVD process: 1) metal species with attached organic ligands approaches substrate surface, 2) adsorption occurs on substrate surface, 3) heat causes decomposition and organic ligand becomes detached from metal species, 4) diffusion of metal species along substrate surface, and 5) nucleation of thin film

Today MOCVD is a widely used thin-film fabrication technique in both research and industrial settings. Various compound semiconductor materials such as GaAs, GaN, InP, etc.,[2–5] for modern electronics applications as well as carbon (C)-based nanomaterials all heavily use MOCVD techniques. The growth of complex oxide thin films has also seen a wealth of research and commercial interest. Optoelectronic materials such as ZnO,[6,7] dielectric and ferroelectric materials such as $SrTiO_3$ and $BaTiO_3$,[8–13] and high-temperature superconducting materials such as YBCO[14,15] have also been developed and are being studied using MOCVD reactor systems.

Why MOCVD? MOCVD as a deposition technique has been established as a desirable method for the growth of semiconductor and complex oxide thin films thanks to its lower reaction temperatures and high throughput. MOCVD requires the use of highly optimized flow reactors, high-precision flow and temperature control, and quick response of controlling components. This requirement allows for the potential of high control of thin-film microstructure, composition, and application.[1–16] Challenges faced by fabrication of thin films by MOCVD primarily attributed to the complex nature of the gas flow and chemical reactions occurring in the reactor chamber at the substrate surface. A substantial amount of research has been dedicated to optimizing reactor and system designs, as well as metalorganic precursor chemistry and delivery methods, in efforts to obtain high-quality thin films with controllable microstructure, composition, and physical properties.

1.2 MOCVD Reactor Designs

1.2.1 Hot- and Cold-Wall Reactors

Control of the temperature environment is a critical aspect of all MOCVD reactors. Although there are many more variations of reactor designs than can be feasibly dealt with in review, temperature control in reactors mainly falls under either hot- or cold-wall system designs. Hot-wall designs refer to reactor environments that are isothermal environments that easily accommodate simultaneous deposition on multiple substrates and have been preferred in the growth of oxide materials with poor thermal conductivity, which require more complex heating equipment than in cold-wall reactors.[17] Reactors with hot-wall designs, while exhibiting better control of temperature distribution and of generally simpler construction, have been noted as suffering from greater maintenance demands due to parasitic deposition of precursor materials on all reactor surfaces as well as lower conversion efficiency of precursor materials in multiple substrate holder systems.[18,19]

Cold-wall reactors, conversely, usually maintain a stage or susceptor that is heated inside of the reactor as the deposition site. The walls and surrounding equipment are still heated beyond the evaporation/sublimation temperature to prevent condensation of precursor materials and to reduce the thermal gradient created by the substrate heater, but they are not heated to match the temperature of the susceptor. Since deposition occurs mainly at the heated substrate and not on the reactor walls, maintenance is simpler and less frequent than that of the hot-wall reactor. Although temperature control is more complex in cold-wall reactors from an engineering perspective, due to incorporation of electrical elements on the interior of the reactor, the reduced temperature environment allows the use of cheaper feed-through and connection material elements.

1.2.2 Horizontal Reactors

Horizontal reactor designs for MOCVD of thin films are favorable because of their simpler structure and relative ease of flow path compared with vertical reactor designs. Horizontal reactors have many variations, including hot- and cold-wall designs,[20] and various geometries, a few of which are represented in Fig. 2.

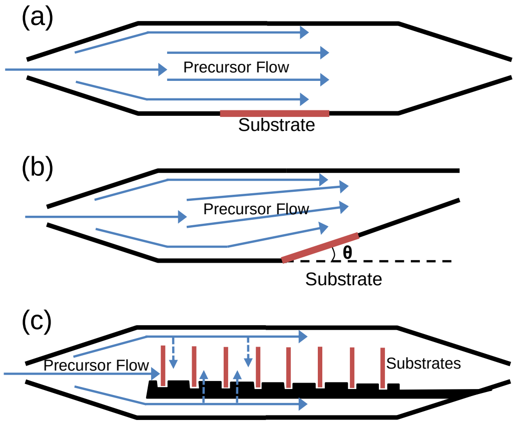


Fig. 2 Common horizontal reactor tube designs: a) flat substrate, b) tilted substrate, and c) vertical substrates

The main challenges faced by horizontal reactor designs is in obtaining uniformity in thin films. Horizontal reactors without an inclined surface similar to Fig. 2a have been shown to produce films with highly anisotropic growth rates with respect to distance from the inlet precursor source.[19,21–23] To combat this, inclined substrate, shown in figure 2b, and rotating substrate variations have been produced that add more complexity and cost to the system but significantly improve film uniformity across a wafer surface.[19,21–23]

1.2.3 Vertical Reactors

Vertical MOCVD reactors have attracted much attention because of their potential for higher deposition rate, efficiency, and uniformity due to deposition at a stagnation point of flow within the reactor. The stagnation point occurs when the impinging gas flow is in the normal direction to the surface of deposition and the local velocity of the flow at this interface is zero.[24,25] Because of the more complex flow path through a vertical reactor compared with horizontal variants, optimization of deposition uniformity has included deep modeling and experimental studies with respect to reactor geometry, temperature distribution, gas velocity, and flow regimes, among many others. Several variations of vertical reactor showerhead designs are presented in Fig. 3.

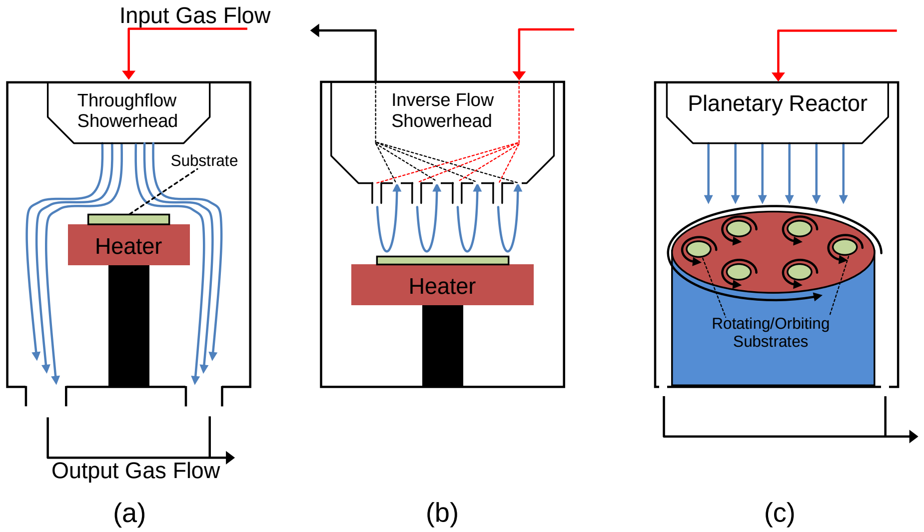


Fig. 3 Select vertical reactor designs: a) conventional showerhead, b) inverse flow showerhead,[26] and c) vertical planetary reactor[19]

Gas-flow studies performed for the optimization of MOCVD systems have been carried out by both simulation and empirical studies. Fluid-dynamics simulations provide a crucial, cost-effective method for optimizing reactor geometries and process conditions for successful deposition of high-quality thin films. Several showerhead designs, such as those presented in Fig. 3, are also simulated using these method and aim to produce vortex-free flow patterns.[26–31] Empirical studies of gas flow through reactors are usually conducted using a technique called flow visualization, which uses TiO_2 particles illuminated by laser light to produce visible flow of gas through the reactor.[24,25,32–34] These studies are used to supplement initial simulations with testing to remove dead spots and flow recirculation that disrupts the laminar flow of precursors through the chamber and increases the residence time of waste products from deposition reactions in the reactor, which is a significant factor to consider if the utilized precursor chemistry contains the potential for C contamination of the desired thin film.[19] Laminar flow is a term used to describe gas flow that does not contain recirculation currents or crossing flow in a gas stream and results in a flow that is orderly and not turbulent or chaotic. The condition for laminar flow has been cited in MOCVD literature as the ratio of inertial forces to viscous forces, also known as the Reynolds number, less than 1,000,[14] but this requirement becomes much more complex with the geometry and temperature gradients that exist in most MOCVD reactors.[24,25,29,35]

1.3 MOCVD Precursor Delivery

MOCVD precursors have a notable advantage over traditional CVD precursors in their lower sublimation and decomposition temperatures (200–800 °C). This allows for lower-cost reactor components that do not require higher temperature stability and can be built with an overall less-complex design. Precursor selection and design is one of the most integral aspects of CVD processes, and the complexity is such that a comprehensive view is beyond the scope of this report. There are many excellent review sources that introduce precursor chemistry and the innovations that have been made in this field.[3,36–40] There are several methods with many variations of delivery of precursor materials for MOCVD, all of which have advantages and limitations associated with their implementation. The main concerns in MOCVD precursor delivery are with efficiency, compositional control, and microstructural quality. Because metalorganic precursors are often very expensive, research efforts focused on efficient usage and maximizing yield are crucial to the successful implementation of MOCVD research and development. Methods of delivery must also give adequate control over the composition, microstructure, and high reproducibility of selected thin-film materials to be viable processes for materials research and production of device components.

1.3.1 Liquid Injection

Liquid injection of metalorganic precursor materials is a delivery system in which either a continuous stream or pulsed delivery of liquid precursor is added to a carrier gas flow before being converted to vapor phase and impinging on the deposition surface. Because the precursor materials are not evaporated directly from the source where they are stored, this technique has a great potential for increasing efficiency in the usage of precursors. When the source supply is heated to evaporate the precursors prior to transfer, decomposition and degradation can occur within material left in the source after deposition, which could result in decrease in precursor performance and increase production costs.[41] An insightful introductory review of liquid precursor delivery equipment and commercial suppliers is detailed by Krumdieck.[19] In general, liquid injection employs a variety of delivery mechanisms, such as syringe pumps, high-speed on/off valves, liquid mass flow controllers, and liquid pumps. An example of a liquid injection delivery system is presented in Fig. 4.

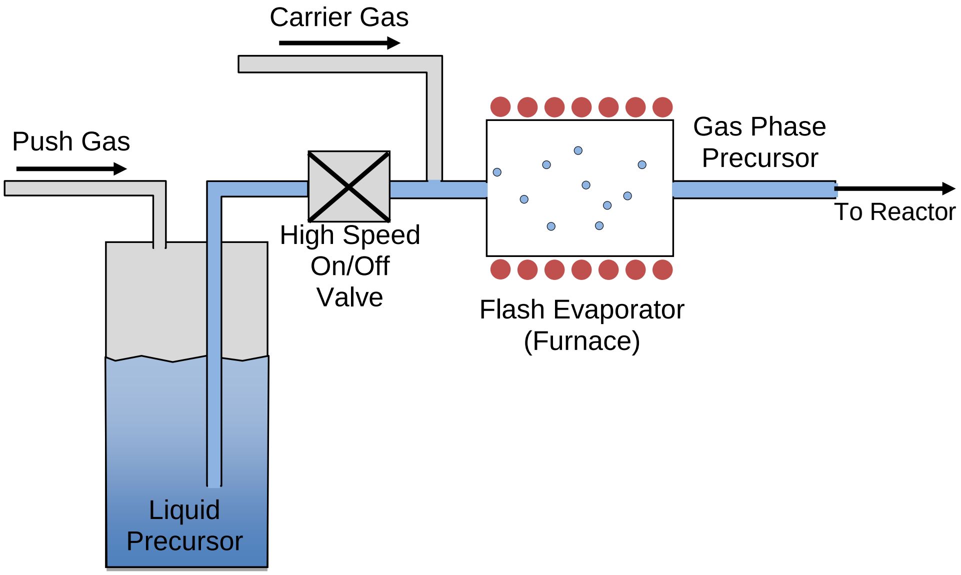


Fig. 4 Liquid injection delivery system

Pulsed liquid injection is also used for its potential to precisely control mass flow of precursors through the reactor, which is limited mainly by the precision of the equipment that supplies the precursor volume in each pulse. This presents an advantage of control in the transportation of precursor mass over conventional bubbler supply techniques.[42,43]

Although the liquid-injection method adds an element of efficiency and control, it can also add complexity in the control of composition and microstructure of the thin film during deposition, especially in heterometallic films, such as $BaTiO_3$ and compound semiconductors, when using more than one precursor source.[14,44–46] Using more than one precursor source with liquid injection requires knowledge of the complex interactions between precursor materials with differing volatilities, vapor pressures, and decomposition reaction times at the surface. This issue has prompted research and development of heterometallic single-source precursors. Liquid injection without a separate evaporation step prior to introduction in the reactor also carries the risk of large droplets that are not decomposed quickly enough and impact the surface, causing anisotropy in the thin film. While direct liquid injection can refer to the delivery of a liquid state of small mass of precursor materials into an MOCVD reactor, wherein evaporation and decomposition occurs due to a combination of the reduced pressure environment and the high temperature at the deposition surface, liquid injection is often combined or supplemented with aerosol and flash evaporation delivery techniques, which are discussed in the next sections.

1.3.2 Aerosol Delivery

A variation of the liquid-injection delivery is aerosol delivery technique, also known as "aerosol-assisted MOCVD", which delivers liquid precursor materials by first separating a liquid volume into "droplets" that can be combined with a carrier gas flow.[47–49] A simple visualization of this is by the use of an ultrasonic source that acts as a nebulizer, shown in Fig. 5. The vibrations from the ultrasonic source release a steady stream of droplets from the surface of the precursor source liquid that have a much higher vapor pressure than a larger volume of liquid due to their greater surface-area-to-volume ratio.[19]

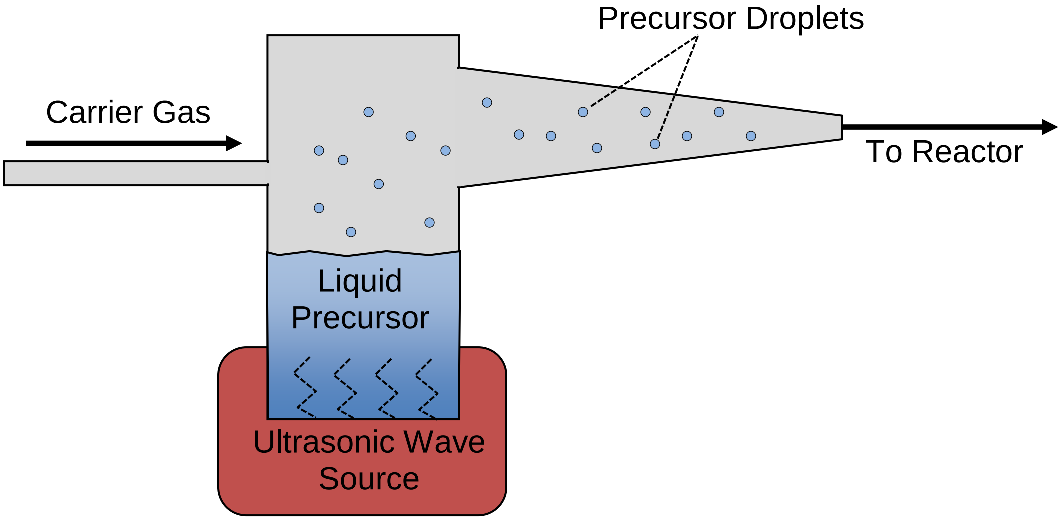


Fig. 5 Nebulizer aerosol delivery of liquid precursor

Ultrasonic sprays are also used to generate precursor droplets small enough to evaporate quickly upon introduction to the reactor.[38,50,51] This technique relies on the high-frequency vibration to form the droplets in the nozzle. Without this vibration, the shear forces on the liquid sheet spray that arise from the pressure differential are not sufficient to break the surface tension of the liquid and will result in a persistence of the liquid state of the precursors. Ultrasonic sprays generate these droplets that can evaporate in the low pressure of the chamber, or by pyrolysis when in the vicinity of the heated deposition surface.

1.3.3 Flash Evaporation (Pyrolysis and Photolysis)

Flash evaporation employs an intermediate heat source to liquid or even solid precursor materials to generate a vapor prior to delivery to the heated susceptor. There are many variations of the flash evaporation technique, including reactions that can occur either in the reactor or upstream in the delivery lines.[52–54] Flash evaporation mechanisms mainly fall into 2 categories: pyrolysis and photolysis. Pyrolysis describes a reaction in which a small volume of precursor material in a carrier gas flow is rapidly heated to evaporation before deposition. This method of delivery can use heated sections of delivery lines or tube furnaces, which means that it can be readily incorporated into both hot- and cold-wall reactor designs since hot-wall designs generally use tube furnace reactors. Photolysis describes the use of an ultraviolet (UV)-range light source to break the bonds of intersecting liquid or solid precursor flow, evaporating or decomposing the metalorganic species near the heated susceptor for deposition. This technique has also been called "laser-assisted CVD".[54] One challenge met with photolysis reactions is that reports have indicated C incorporation into the thin films to be a persistent challenge.[45,55]

1.3.4 Bubbler Evaporation/Sublimation Delivery

A typical method of precursor delivery involves the use of a bubbler setup and an inert carrier gas such as nitrogen or argon (Ar) to control a flow of vapor-phase precursor materials into a reactor, as shown in Fig. 6. A clear advantage of this method is that it does not require the precise, periodic delivery of a liquid or solid material into a heating environment for evaporation or sublimation, unlike liquid injection and flash evaporation techniques. The removal of a requirement to rely on precision timing and mass controls in favor of a constant flux of precursor materials reduces cost and the complexity of deposition.

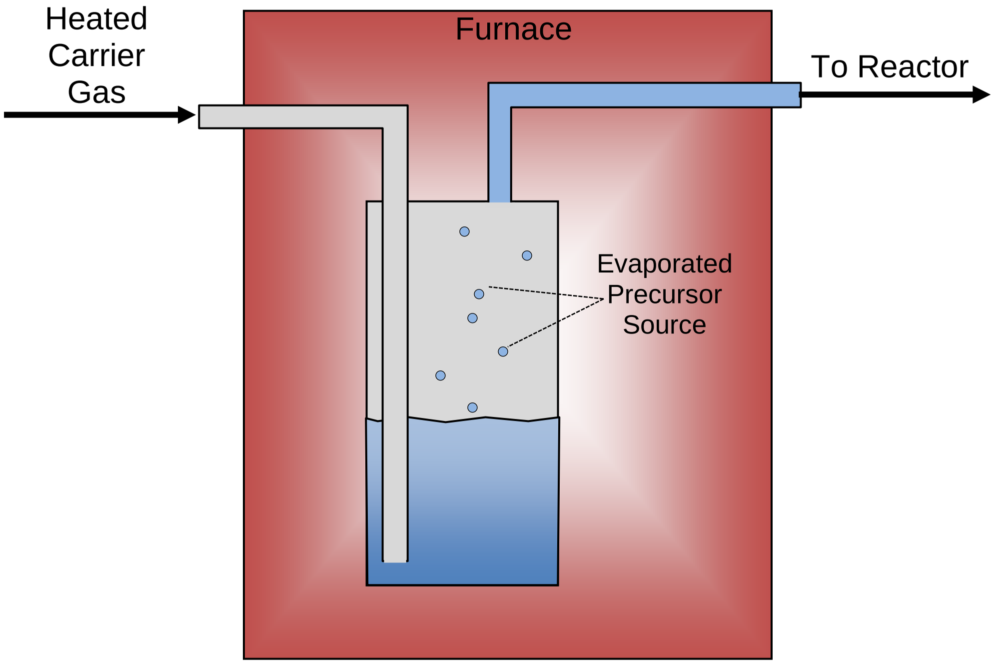


Fig. 6 Bubbler delivery of precursor materials

A significant limitation met with this technique has been in control of composition and reproducibility. Using a constant flow of carrier gas to deliver metalorganic precursors ignores the inevitable fluctuations in precursor yield and thermal stability. Also, changes in the flow of gas itself can produce differences in the pressure of a bubbler and lead to complex variation in the yield of a precursor. UV spectroscopy techniques have successfully provided a method for straightforward operator control of the precursor mass flow rates of multiple source component oxide thin films, which is used in the US Army Research Laboratory's (ARL's) MOCVD system and discussed in the next section of this report.[56,57]

1.4 ARL's Gen 2 MOCVD System

The MOCVD system built at ARL was the result of a technology transfer collaboration with the California Institute of Technology, referred to here as the Gen 1 system. An in-depth view of the development and features of the Gen 1 system is available through the meticulous work and documentation of the doctoral thesis of Ashok Burton Tripathi, whose efforts remain invaluable to the modification and maintenance of the MOCVD system built at ARL.[15] ARL's MOCVD system, referred to the Gen 2 system, is fairly similar in design, though the implementation has included significant modifications of various aspects of the system for the dedicated fabrication of tunable dielectric microwave materials, including most aspects of temperature control in the reactor and supply lines, reactor geometry, vacuum equipment, and sample loading mechanisms. The Gen 1 and 2 systems have a number of advantages as MOCVD systems, most notably in the in situ monitoring for precursor delivery control. Solid-state precursors, specifically the metal β-Diketonate complex organic precursors used in this study, have a unique absorbance in the UV wavelength region, so their individual vapor phase concentrations in a carrier gas stream can be monitored using a UV spectrometer. This in situ UV spectroscopy was detailed specifically for use with oxide β-Diketonate complex organic precursors used in the fabrication of high-temperature superconducting oxide thin films, and was later adapted for use in fabricating dielectric complex oxides such as $SrTiO_3$ and $BaTiO_3$.[15,56] When the precursor materials are present in an inert carrier gas stream, there is a measureable absorption in the UV range. By measuring the relative change in absorption using a wavelength where the absorption magnitude is maximum, precursor concentration can be calculated using the Beer-Lampert relation:

$$A = \varepsilon C \ell, \tag{1}$$

where A is the total absorbance, or the fraction of radiation absorbed at the measured wavelength; ε is the calculated molar extinction coefficient for the given precursor species; C is the carrier concentration; and ℓ is the path-length, or the measured distance that the UV light travels through the gas medium being measured. The in situ monitoring technique allows for a much tighter control over the mass flow and ratio of active precursor species that is otherwise very difficult to obtain using bubbler sublimation for precursor delivery. It provides a great potential for controlling multiple component thin-film stoichiometry in lieu of techniques that would require the user to prepare the stoichiometry of as-deposited thin films by altering the active precursors prior to deposition.

The challenges that the Gen 2 system has faced since its inception deal mostly with film uniformity and contamination at the interface of deposited strontiuim titanate (STO) thin films. As shown in Fig. 7, when the main lines are opened to the chamber, debris flows through and coats the sample anisotropically. With the interface consistently compromised, subsequent efforts to grow films of high quality are unsuccessful. Since this phenomenon was observed to occur at the moment the gas lines were initially opened, it was hypothesized that one might only need to protect the sample from the initial debris to overcome this contamination.

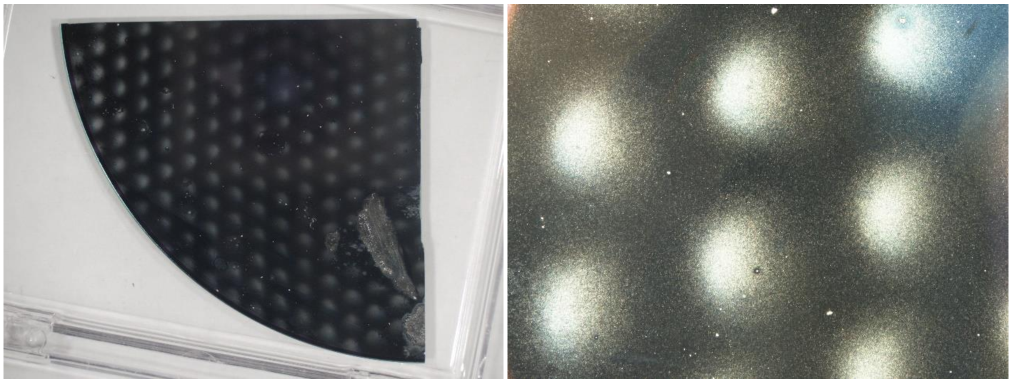


Fig. 7 Platinized silicon (PtSi) substrate surface patterned with debris from gas lines prior to film deposition

Another challenge was met in that the films that were produced were anisotropic in thickness across the substrate, as visible in Fig. 8. Initially it was not known whether this phenomena was coupled with the interface contamination or, possibly, an anisotropic temperature distribution on the substrate heater, but it was later observed that the anisotropy and interface contamination were independent phenomena. The edges of the samples, as shown in Fig. 8, were patterned with inhomogeneous film distribution, which was confirmed to be of varied thickness.

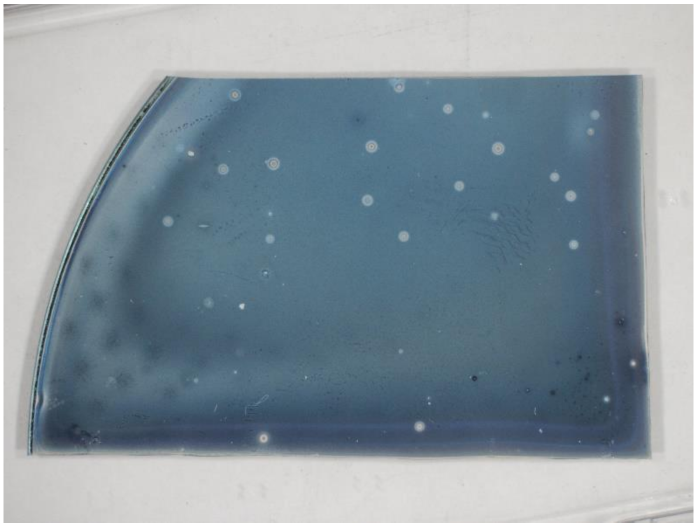


Fig. 8 Film inhomogeneity over substrate surface for STO thin film grown on PtSi before hardware modifications. Edge effects can be seen on the surface of the as-deposited sample.

2. Proposed MOCVD Hardware Modifications

In attempts to protect the sample from the consistent debris that escapes onto the sample heater prior to film deposition, it was decided that a loading chamber would be attached to the main chamber to hold the sample during predeposition processes. Figures 9a and 9b depict the chamber before and after the proposed modification. While the sample was contained in a separate chamber prior to deposition, it was believed that any contaminants from the gas lines could be evacuated through high-temperature baking and inert gas flow evacuation, and would therefore not be deposited onto the interface, which would allow for the film to grow on a "clean" sample surface. After clearing the entering gas lines of debris, the samples could then be transported from the load chamber to the main chamber via a wobblestick load arm, whose position and direction could be slightly adjusted by the user due to a flexible segment in the equipment design, which is illustrated in Fig. 10.

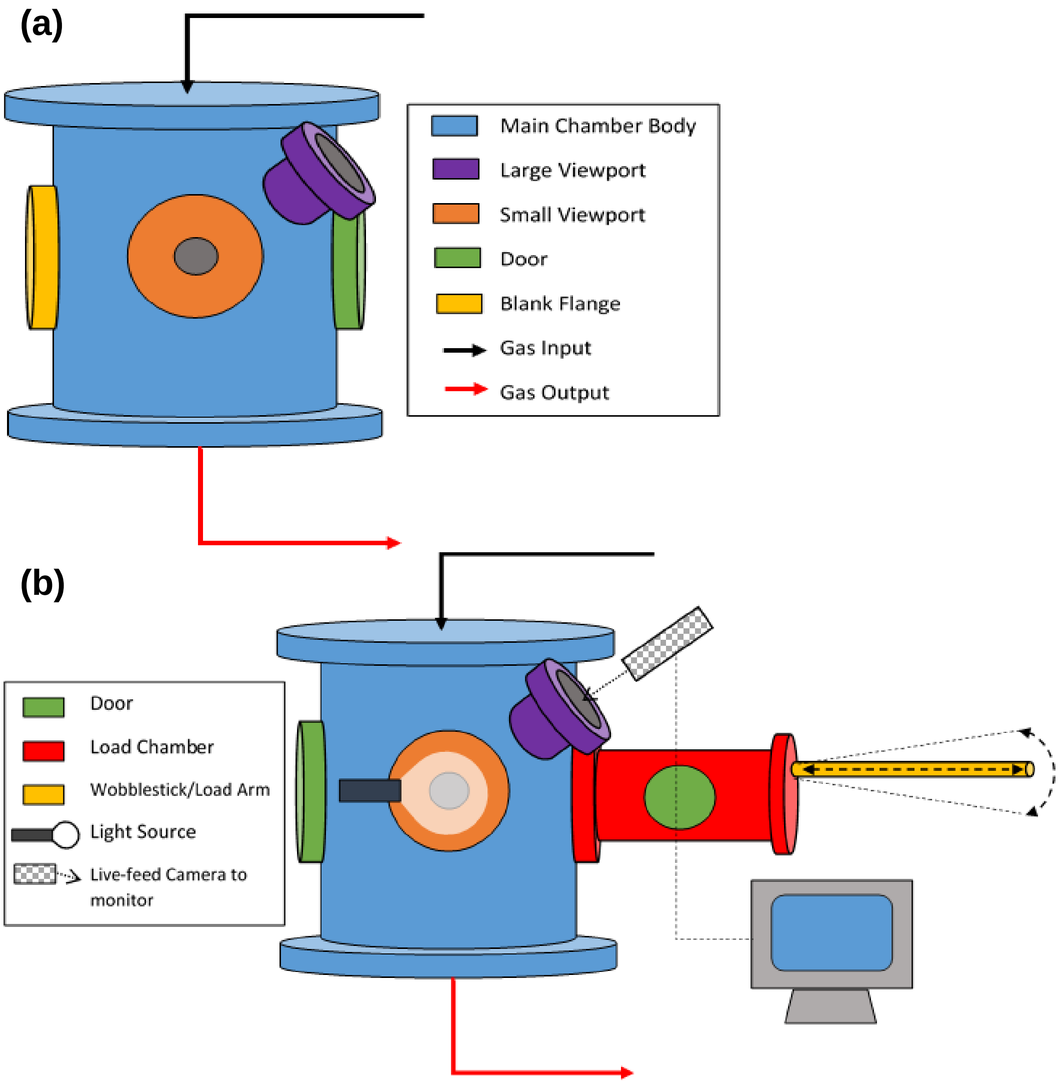


Fig. 9 a) Original main chamber setup and b) the chamber setup after the proposed modifications

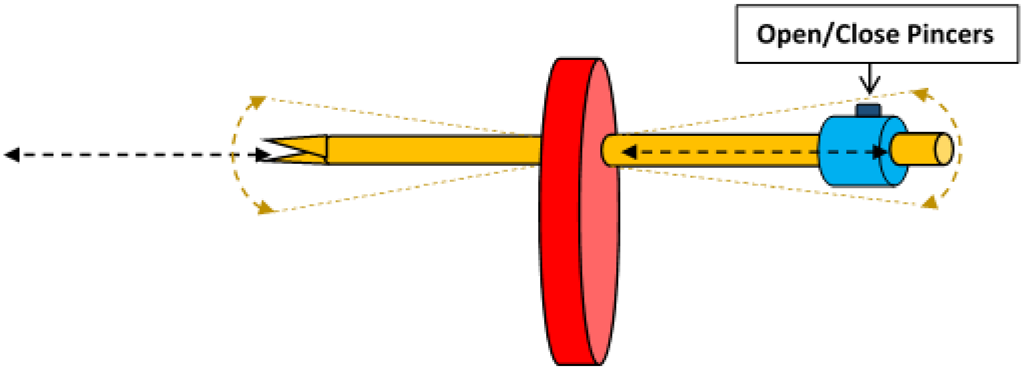


Fig. 10 Load arm used to transport sample from load chamber to main growth chamber

It was observed that to successfully transport samples in between chambers onto a sample heater, the ability to view the position of the sample during transport is required, which produced some difficulty due to the original design of the main chamber. Sample transport needed to be precisely controlled because the gap between the showerhead and the ceramic heater was only 2 inches high, while the tip of the sample transporter was 1.5 inches high, giving a small margin for user error. To overcome this obstacle, it was proposed that a camera be positioned to capture a view of the sample heater through one of the main chamber viewports. This camera could then provide a live feed to a monitor that would be watched by the user during the transport of the sample between chambers. The live-feed camera setup is illustrated in Fig. 9b.

3. $SrTiO_3$ Deposition Conditions

An STO thin-film sample deposited after hardware modification is the subject of comparison to determine the impact of the hardware modifications on the quality of thin films produced by the Gen 2 system. Several STO films were grown prior to hardware modifications and were available for comparison; however, prior to hardware modification, energy dispersive spectroscopy data suggested that the ratio of strontium (Sr) to titanium (Ti) (ideally 1:1) could not be achieved, and neither are STO thin films in a strict sense, but the same precursor sources and similar processing conditions were maintained before and after hardware modifications.

Deposition of the STO thin films on commercially available platinized Si substrates, Pt(150 nm)/Ti(50 nm)/SiO_2/Si and abbreviated as PtSi, were conducted with a susceptor temperature of 620 °C and reactor pressure of 15 Torr for 120 min. The walls and precursor gas supply lines were maintained near 250 °C to prevent condensates. Solid-state β–Diketonate complex precursors Bis(2,2,6,6-tetramethyl-3,5-heptanedionato) purchased from Strem, abbreviated here as Sr(tmhd), and titanium(IV) diisopropoxidebis(2,2,6,6-tetramethyl-3,5-heptanedionate) purchased from Sigma-Alrich, abbreviated here as Ti(tmhd), were used in all depositions. The Sr precursor temperature for sublimation was approximately 275 °C, while the Ti precursor sublimation temperature setting was 105 °C during deposition. Individual precursor mass flow was controlled by the in situ UV spectrometer feedback loop system. A constant precursor mass flow of 15 µmole/min was used for deposition, with a mole ratio of 95% Sr/5% Ti and a constant Ar carrier gas flow of 6,000 standard cubic centimeters per minute (sccm). A shroud flow to promote laminar flow and prevent recirculation of 5,000 sccm was used, along with a supplemented O_2 flow of 1,000 sccm to mitigate oxygen vacancies that result in nonstoichiometry of the films. Prior to sample loading and deposition, the reactor and precursor supply lines were baked at 250 °C for at least 4 h with a total Ar carrier gas flow of 5,000 sccm to remove precursor condensates from the gas lines and showerhead.

4. Results and Discussion

4.1 MOCVD Hardware Modifications

The proposed hardware modifications were successful, and a light source was added to the system to aid in visibility for the user during sample transport. The addition of the live-feed camera also allowed the user to capture stills of the sample during deposition, which provided the users with additional visual data throughout the entire deposition process. Selected stills are shown in Figs. 11a and 11b.

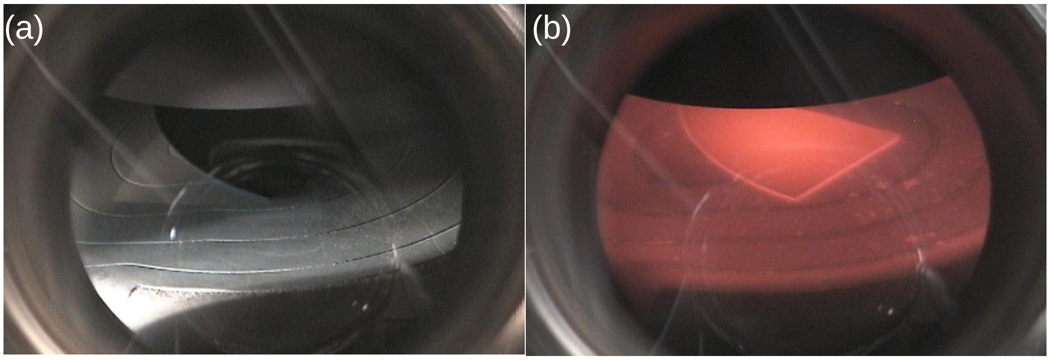


Fig. 11 Selected images of samples taken by live-feed camera: a) PtSi sample substrate seen with light source prior to deposition and b) PtSi substrate during deposition of STO film

After installation of the load chamber and wobblestick, film quality had a notable visual increase in quality. Figures 12a and 12b compare the visible surface of as-deposited thin films prior to and after the hardware modifications, respectively. The dotted pattern of surface contamination that covered the substrate surface prior to the hardware modifications (Fig. 12a) is not present in Fig. 12b.

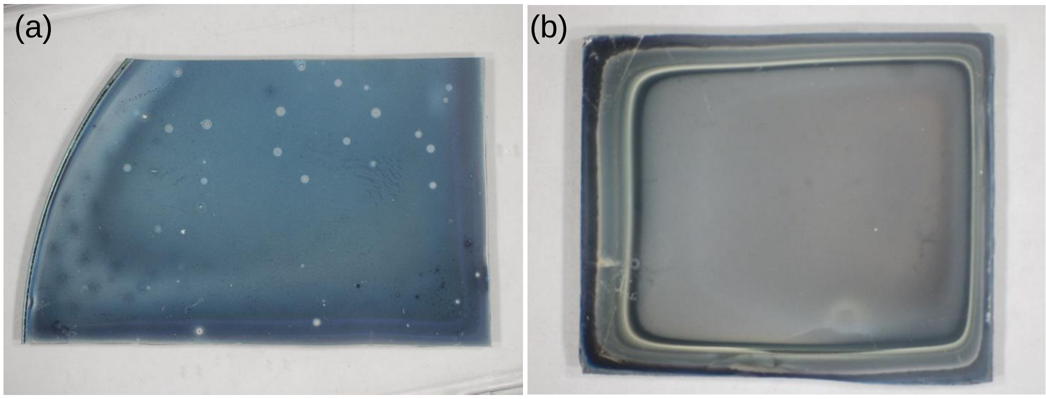


Fig. 12 Example surface of as-deposited STO film grown on PtSi substrate a) before and b) after hardware modifications

Although the dotted contamination pattern was removed, the edge effects of inhomogeneity were still present in the as-deposited STO samples. To investigate the issue of anisotropy further, studies in the temperature distribution of the sample heater and the gas interaction at the surface were required. The elimination of the showerhead debris as a contributing factor allowed for a focused optimization study on growth parameters and processes in the STO thin-film fabrication for ARL's Gen 2 system.

4.2 Topography and Microstructural Characterization

4.2.1 X-ray Diffraction (XRD)

The glancing-angle XRD in Fig. 13 data shows a peak that is consistent with the (110) orientation of STO. Because of the close lattice parameters of STO and Pt, there may be overlapping (111) and (200) substrate and STO thin-film peaks, and further investigation is required to confirm.

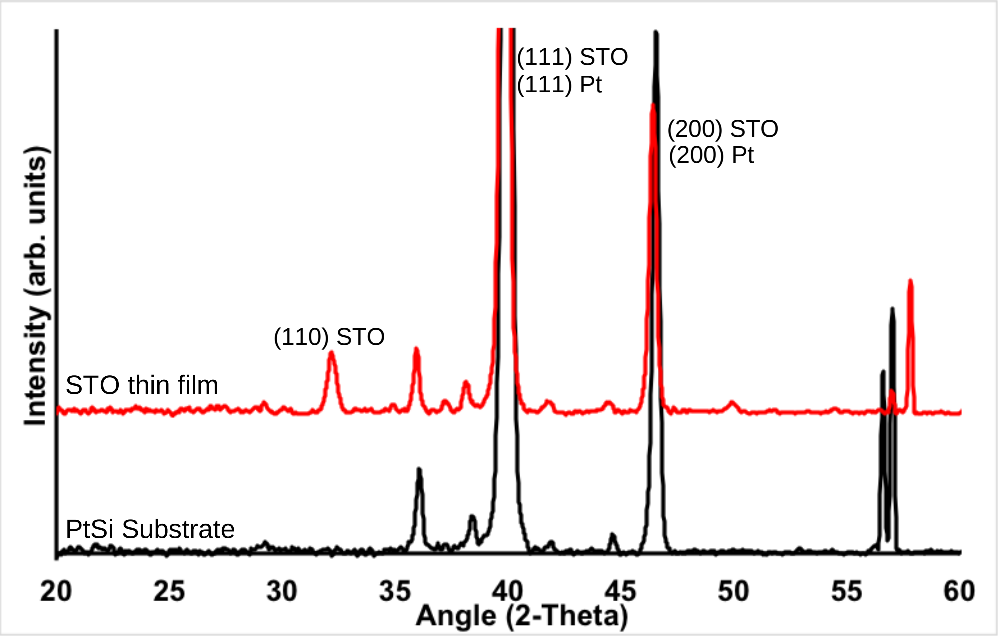


Fig. 13 Glancing-angle XRD scan of PtSi substrate (black) and as-deposited STO thin film (red) after hardware modifications were performed

4.2.2 Scanning Electron Microscopy (SEM)

SEM cross-sectional images of the STO thin film were compared before and after hardware modifications were performed to investigate the impact of the hardware modifications on the homogeneity and microstructural film quality. The SEM data suggests that delineation between layers was notably improved, though there was a significant amount of inhomogeneity in film thickness across the substrate, as seen in the STO layer in Fig. 14b. The improvement in the interface quality between the PtSi substrate and the STO thin film in Fig. 14b is expected to result from the absence of the showerhead contamination that exists in the STO films grown prior to hardware modifications, presented in Fig. 14a.

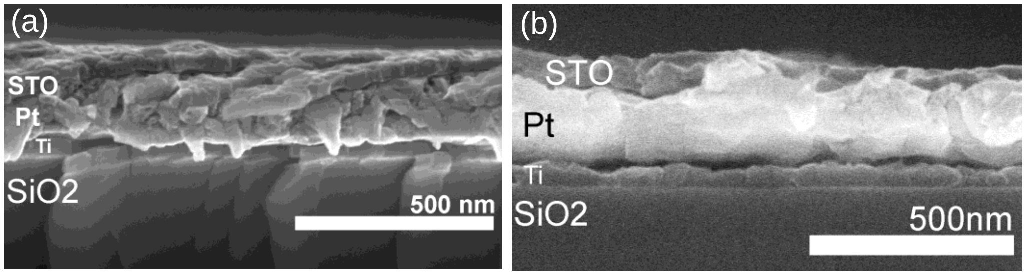
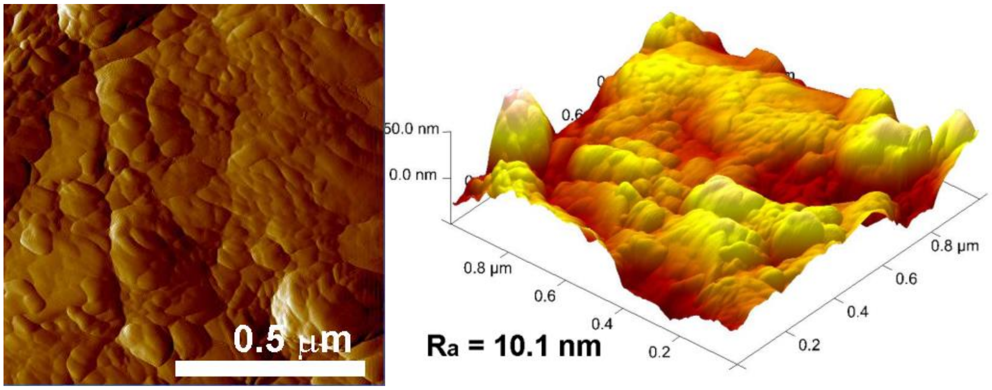


Fig. 14 SEM cross-sectional images of STO thin films deposited using Gen 2 system a) before and b) after hardware modifications

4.2.3 Atomic Force Microscopy (AFM)

AFM micrographs for the as-deposited STO thin film after hardware modifications were taken near the center of the substrate, and the average roughness (R_a) was determined to be 10.1 nm (Fig. 15). Topography suggests a dense, polycrystalline microstructure of the STO thin film was obtained. The thin-film area near the edge of the substrate, which SEM data suggests thinner and less homogeneous STO thin film, was not investigated due its anisotropy and overall lower film quality.



(a) (b)

Fig. 15 a) 2-dimensional and b) 3-dimensional AFM scans of 1-µm^2 area for STO thin film fabricated after hardware modifications were made. Average roughness (R_a) was calculated as 10.1 nm.

5. Summary and Conclusions

Investigations were made in attempts to improve the compositional and structural quality of STO films as grown by ARL's Gen 2 MOCVD system as well as the homogeneity over sample area. While the interface contamination was eliminated with the introduction of the hardware modifications and reactor cleaning process, the inhomogeneity of the STO thin films persisted, which requires further investigation of the process parameters. Because of the many variables involved in the MOCVD process, spanning hardware, user software, and controllable growth parameters, there is still a notable element of irreproducibility in the STO films grown by the Gen 2 system. In the future, many more investigations must be conducted into the role of each of the controllable growth parameters, with the goal of optimization and stabilization across depositions.

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List of Symbols, Abbreviations, and Acronyms

AFM	atomic force microscopy
ARL	US Army Research Laboratory
CVD	chemical vapor deposition
MOCVD	metalorganic chemical vapor deposition
PtSi	platinized silicon (Pt/Ti/SiO_2/Si)
PVD	physical vapor deposition
sccm	standard cubic centimeters per minute
SEM	scanning electron microscopy
STO	strontium titanate ($SrTiO_3$)
XRD	X-ray diffraction

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