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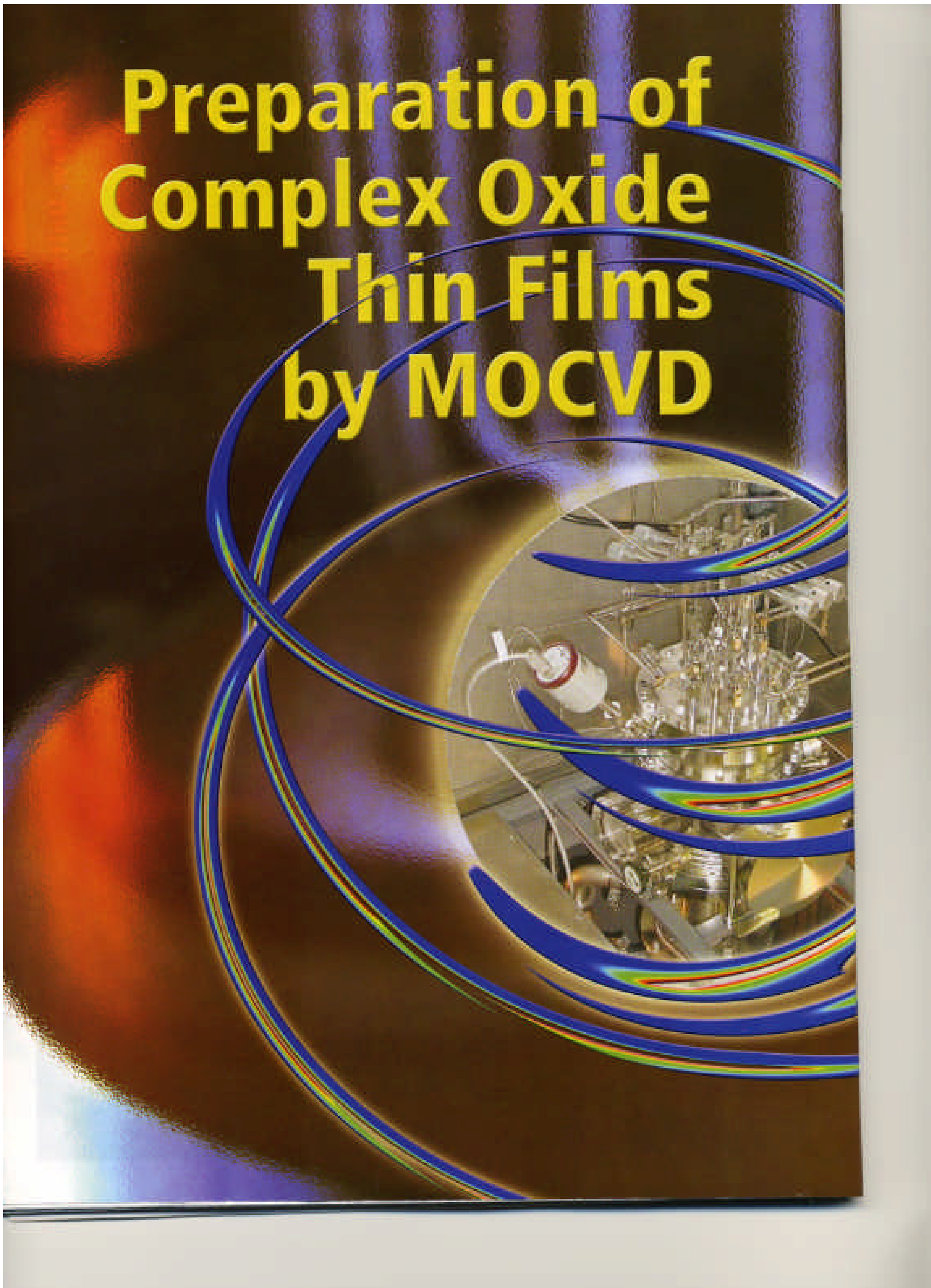

Preparation of
Complex Oxide
Thin Films
by MOCVD

By N.M. Sbrockey, J.D. Cuchiaro, B.H. Hoerman, L.G. Provost, C.E. Rice, S. Sun and G.S. Tompa

Structured Materials Industries, Inc. Piscataway, NJ

The complex oxides are compounds of two or more metals and oxygen. Many of these materials have unique and valuable properties, including ferroelectric, piezoelectric, pyroelectric and electro-optic behavior. Their electrical properties can include insulating, semiconducting, conducting and even superconducting behavior. There is rapidly growing interest to produce thin films of complex oxides for application in sensors, microelectronics, MEMS, optics and electro-optic devices. **Table I** lists some technologically important oxide materials that have been investigated by the authors, along with their respective applications. See Reference [1] for further information on complex oxides and their properties and applications.

Depositing thin films of the complex oxides, with the necessary control of composition and properties, presents many unique challenges. Because of their complex composition, we not only need to maintain proper oxygen stoichiometry, but also the proper ratio of metal components. Because of the applications that these materials are used in, we need to precisely control thickness, uniformity, crystallinity and crystal orientation of the films. In this paper, we describe these challenges, and how they are met using a metal organic chemical vapor deposition (MOCVD) system designed specifically for complex oxide thin films.

Chemical vapor deposition (CVD) generally refers to thin film deposition processes for which the source materials are introduced in the form of gases. These gaseous source materials undergo chemical reactions in the process of forming a coating. MOCVD is a subset of CVD, for which the source materials are metal organic compounds. Further information on CVD and MOCVD can be found in references [2-4]. The other major category of thin film deposition techniques are known as physical vapor deposition (PVD) processes. PVD generally refers to processes for which the source materials are introduced in the form of solids. These solid sources undergo primarily physical changes in the process of forming a coating. Examples of PVD processes include sputtering, evaporation and laser ablation.

Table I. Examples of Technologically Important Oxide Materials.

End Use	Example Materials
High dielectric constant materials	$BaTiO_3$, $SrTiO_3$, $Ba_xSr_{1-x}TiO_3$, ZrO_2, HfO_2
Ferroelectric materials	$SrBi_2Ta_2O_9$, $Pb(Zr_xTi_{1-x})O_3$, $CeMnO_3$
Electro-optical materials	$LiNbO_3$, doped ZnO
High Tc superconductors	$YBa_2Cu_3O_x$
Transparent conducting oxides	In_2O_3:SnO_2, doped ZnO
Thin film battery electrodes	$LiCoO_2$
Hydrogen barrier layers	Al_2O_3

The most often cited advantage of using CVD is the ability to deposit thin films conformally, onto three dimensional objects or over topography on planar substrates. However, there are many other significant advantages of CVD (and in particular MOCVD) to deposit thin films of the technologically important complex oxides. MOCVD is a very flexible technique, capable of accommodating a wide range of substrate shapes and sizes, as well as a variety of thin film compositions. MOCVD can produce a variety of device structures, including layers with abrupt interfaces or graded composition profiles, on the same substrate and often in the same process run. MOCVD is readily scaleable to large area substrates and to high volume production. With suitably engineered deposition hardware, MOCVD can provide excellent control of film composition, structure, crystal texture and interface chemistry.

Metal Organic Precursors

CVD using inorganic sources is limited to a small range of film compositions, due to the limited availability of volatile source materials. Several of the group IV and group V hydrides are gases at room temperature, and these have enabled the well known CVD processes used in silicon based semiconductor fabrication. Other than a few halides of the transition metals, very few other volatile inorganic CVD sources are available. However, the use of metal organic precursors has extended CVD technology to nearly every element in the periodic table, as illustrated in **Table II**. MOCVD precursors are now commercially available from a number of vendors, specifically synthesized for greater volatility, cleaner deposition and improved thermal stability. See references [5-8] for more information on metal organic precursors for oxide materials.

Metal organic compounds consist of a metal plus an organic ligand. The metal organic precursors used for MOCVD of oxides typically fall into one of three general types, namely the beta-diketonates, the metal alkoxides and the alkylmetals. **Table III** lists selected properties of several precursors commonly used for MOCVD of oxides. The beta-diketonates and the metal alkoxides are typically low vapor pressure liquids or solids at room temperature.These materials must be heated in order to provide sufficient volatility for vapor delivery into an MOCVD reactor.Also for the beta-diketonates and alkoxides, the metal is in the desired oxidation state for the intended film. However, it is generally advisable to provide excess oxygen flow during MOCVD, in order to ensure full oxidation of the film and removal of organics.

MOCVD Reactor Design

A complete production-worthy MOCVD system consists of the MOCVD reactor, the precursor delivery

Table II. Periodic Table of the Elements, illustrating the range of thin film compositions that can be produced by MOCVD. Thin film compositions containing the elements displayed in yellow are compatible with MOCVD technology. Thin film compositions containing the elements displayed in green have been demonstrated in the author's laboratory.

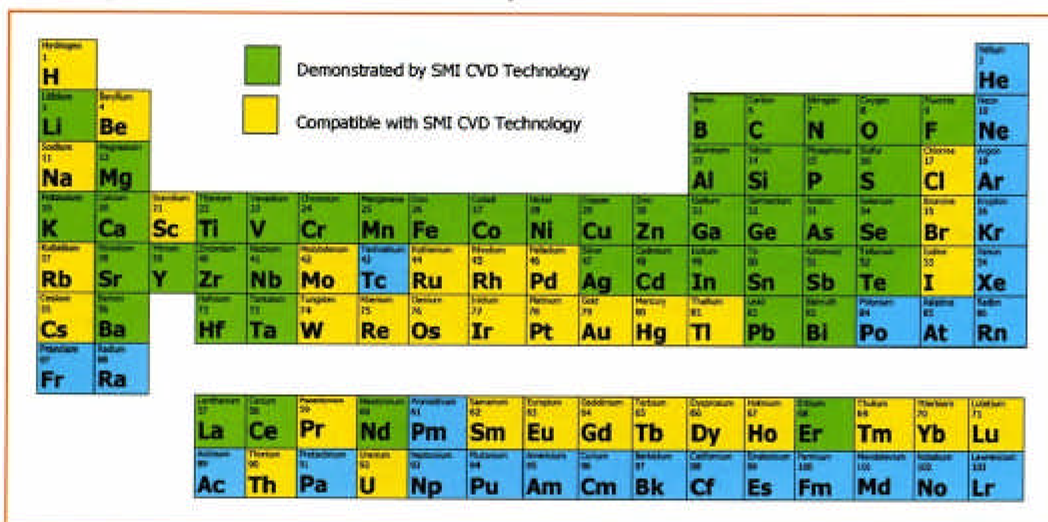


Table III. Examples of some commonly used metal organic precursors and selected properties.

Element	Metalorganic Precursor	Physical State at Room Temp.	Vapor Pressure		Typical Vaporization Method
			Torr	at T(°C)	
Al	Trimethylaluminum	liquid	15.2	30	bubbler
Ba	Barium (II) thd*	solid	0.05	225	flash evaporator
In	Trimethylindium	liquid	5.54	35	bubbler
Pb	Lead (II) thd*	solid	0.1	134	flash evaporator
Sr	Strontium (II) thd*	solid	0.05	230	flash evaporator
Ta	Tantalum (V) ethoxide	liquid	0.1	145	bubbler
Ti	Titanium (IV) iso-propoxide	liquid	1.0	58	bubbler
Zn	Diethylzinc	liquid	21.1	30	bubbler
Zr	Zirconium (IV) iso-propoxide	liquid	5	204	bubbler

*thd = 2,2,6,6 – tetramethyl – 3,5 – heptanedionate

system, the process control system, the vacuum pumping system and the exhaust treatment system. In this article, we will primarily discuss the MOCVD reactor and the precursor delivery system. The optimum reactor design is the one that provides the best control of the deposited film properties, and meets the structural requirements of the device being built. In choosing the appropriate reactor design, we must first consider the overall kinetics of the CVD reactions involved. Low pressure CVD is typically done under laminar flow conditions. A thin boundary layer is present near the surface of the growing film, where the gas velocity is nearly stagnant. The rate of thin film growth will be governed by the slowest step in the overall deposition process. Two limiting cases are possible; either a chemical reaction at the surface of the growing film or diffusion of some species across the boundary layer. **Figure 1** illustrates the typical dependence of deposition rate on temperature observed during CVD. The figure shows the two basic regions of process kinetics. The data on the low temperature (right side) of **Figure 1** indicate "reaction limited" CVD kinetics. The data on the high temperature (left side) of **Figure 1** indicate "diffusion limited" CVD kinetics. Although this is a vast over-simplification of a very complicated process, it is nonetheless a very powerful tool for understanding how CVD reactor design will affect overall process results.

Reaction limited CVD kinetics are generally observed for low temperatures, low pressures and/or low sticking coefficient reactants. Since the deposition rate increases exponentially with temperature, achieving uniform substrate temperature is imperative for achieving uniform film thickness. The following simple calculation illustrates this point. Typically, activation energies for MOCVD reactions range from 1.0 to 3.0 eV. For an activation energy of 2.0 eV, a temperature variation of 2.0°C across a substrate will cause an 8% difference in deposition rate, and therefore deposited film thickness across the substrate. Thus in order to achieve film thickness uniformity of 8% in this case, we would need to keep temperature variation across the substrate to within 2.0°C. The uniformity of gas distribution has less of an effect on thickness uniformity when CVD kinetics are reaction limited. Since precursor molecules arrive at the surface of the growing film faster than they react, there is always a ready supply of reactants near the film surface. Theoretically, there should be no reactant depletion or "loading effect", as long as the total feed rate is sufficient to avoid starvation of the deposition reaction.

Reaction limited CVD processes are typically done in a general class of reactors known as "hot-wall" or "hot-wall tube" systems. An isothermal tube is a very good geometry for achieving temperature uniformity. It is not a good geometry for achieving uniform gas distribution. Therefore, hot-wall tube reactors yield good thickness uniformity only when CVD kinetics are reaction limited. A major disadvantage of the hot-wall reactor design is that the reactor walls get coated at about the same rate as the substrate, since they are at the same temperature. Care needs to be taken so that these wall coatings do not reach sufficient thickness to begin flaking off and generate particulates in the system. This means that a schedule of periodic cleaning must be maintained for a hot-wall CVD reactor, in order to maintain low defect densities for the deposited films.

The other main category of CVD behavior is characterized by diffusion limited reaction kinetics, as shown in the left side of **Figure 1**. Diffusion limited CVD kinetics are generally observed for

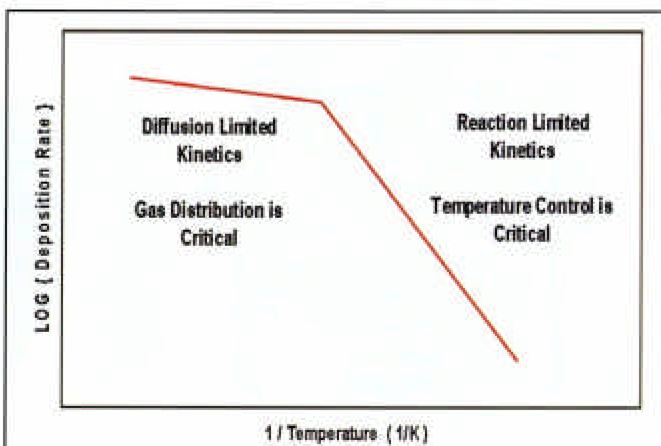


Figure 1. Deposition rate versus temperature behavior typically observed for chemical vapor deposition. The graph indicates the two regions which are usually attributed to diffusion limited kinetics (left side) and reaction limited kinetics (right side).

high temperatures, high pressures and/or high sticking coefficient reactants. The film deposition rate is less sensitive to temperature for diffusion limited kinetics, since reactant molecules are consumed at the surface of the growing film just as fast as they arrive. The small temperature dependence evident on the left side of **Figure 1** is due to increasing gas diffusivity with increasing temperature. Local starvation of the CVD reaction can readily occur when kinetics are in the diffusion limited regime. Uniform gas distribution is essential for obtaining film thickness uniformity for diffusion limited kinetics. If we try to perform a diffusion limited CVD process in a tube reactor, we will get loading effects. A lower deposition rate will occur on the downstream side of the tube, due to reactant depletion. Historically, reactor designs have tried to compensate for this effect by decreasing the cross sectional area for gas flow along the length of the CVD reactor. The increased gas velocity resulted in a decreased boundary layer thickness. The intention was for the shorter gas diffusion distance to offset gas depletion effects.Although many creative designs have been put forth, uniform film thickness over reasonable sized substrates, in a tube reactor, under anything other than reaction limited kinetics, is still very difficult to achieve. Presently, CVD tube reactors are mainly delegated to single component films for which composition and thickness control is less critical, such as SiO_2 or Si_3N_4, and for reaction limited CVD kinetics only.

The situation gets more complicated for deposition of complex oxide materials. In this case, we are essentially doing two or more depositions simultaneously. Any variation in CVD conditions can cause not only a variation in film thickness, but also a variation in film composition. Since the different components of a complex oxide may exhibit widely varying reaction kinetics, we may be doing CVD under reaction limited kinetics for one component and diffusion limited kinetics for another. Because of the end-user's requirements for high deposition rates, substrate temperatures and gas pressures are typically increased, which tends to push the CVD kinetics into the diffusion limited regime. However, other constraints may limit the deposition process to low temperatures, such as protecting device structures already on the substrate. The ideal reactor for MOCVD of complex oxides needs to control film thickness and composition for both reaction limited and diffusion limited CVD kinetics. This means we need both excellent control of substrate temperature and highly uniform gas distribution.

Figure 2 shows SMI's rotating-disk MOCVD reactor designed specifically for complex oxide thin films. The system is characterized by a vertical cylindrical chamber and a horizontal rotating substrate holder. This design is part of a general class of reactors known as "cold-wall" or "warm-wall" CVD systems. The reduced wall temperatures minimize particulate generation and reduce the need for periodic reactor cleaning. The system is designed for uniform thin film deposition, under either reaction limited or diffusion limited CVD kinetics. A proprietary showerhead design is used to achieve optimum distribution of precursor vapors to the wafer surface. The substrate platen is radiantly heated from below. The heater material is selected for compatibility with the process chemistry. Substrate temperature uniformity is ensured by using a multi-zone heater design with independent temperature measurement and control for each zone. The integrated substrate rotation/heater assembly further ensures temperature uniformity by minimizing non-uniform heat losses associated with radiation from the wafer edges and heat conduction down the substrate platen support shaft.

Rotation of the substrate platen provides for even greater uniformity through two independent effects. First, at rotation speeds greater than the thermal time constant of the substrate platen (typically a few 10s of RPM), substrate rotation averages out non-uniformities in heat transfer from the radiant heaters. Secondly, at relatively high disk rotation speeds, the

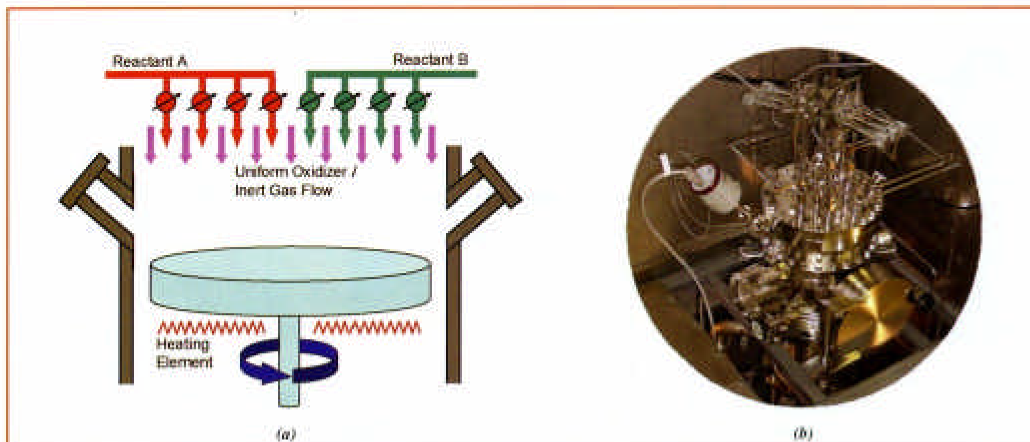


Figure 2. The rotating disk MOCVD reactor which has been designed specifically for complex oxide thin film deposition. **(a)** Schematic illustration of the MOCVD chamber, rotating disk arrangement and showerhead with radial control of precursor flux. **(b)** Photograph of a commercial reactor produced by Structured Materials Industries, Inc (SMI).

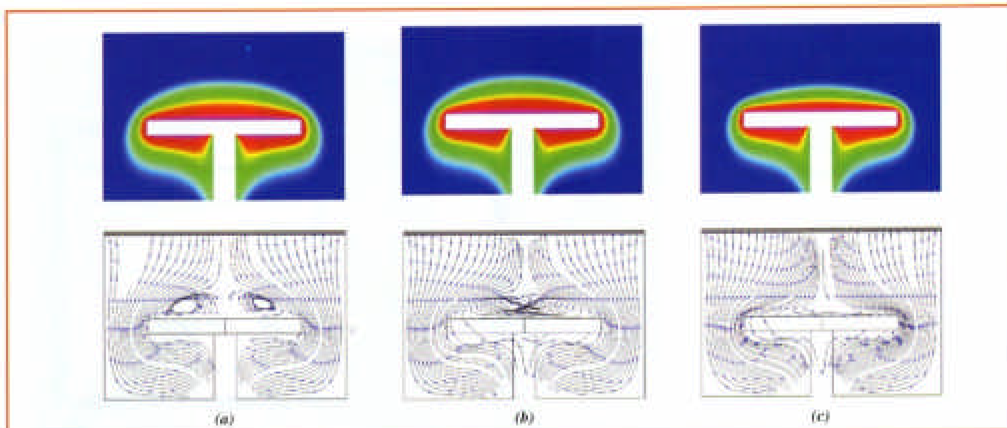


Figure 3. Results of computer simulation of the effect of disk rotation speed on process gas flow. The results shown are for a 5 inch disk operated at 20 Torr total pressure and (a) 0 rpm, (b) 200 rpm, and (c) 750 rpm. Note the absence of gas recirculation above the rotating disk at 750 rpm.

process gases are drawn down to the disk surface by viscous drag effects. Within a specific range of gas pressure, gas flow rate and disk rotation speed, very uniform gas flow can be established across the entire disk surface [9]. This is the basis for the rotating disk reactor design, which has been used extensively for compound semiconductor thin film deposition. When the proper operating conductions are used, disk rotation can eliminate the gas recirculation that is typically observed for flow around a stationary heated disk, as shown in **Figure 3**. Highly uniform gas distribution in a rotating disk reactor has been verified by numerical simulation [10] as well as actual flow visualization [11], as shown in **Figure 4**.

Another advantage of the horizontal disk reactor geometry is that the wafer surface is readily available for in-situ monitoring. In-situ monitoring by optical pyrometer, optical thickness monitoring and spectroscopic ellipsometry are provided for in the design. The optical view ports are designed to be non-intrusive to the CVD process, introducing no perturbations to the process gas flow or to the substrate temperature uniformity. Optical reflectance is a well established technique for in-situ monitoring of film thickness. Spectroscopic ellipsometry provides information on thickness and optical properties of the deposited film, and has been shown to be particularly effective for in-situ monitoring of complex oxides [12]. When monitoring multiple wafers by optical techniques, the observations must be synchronized with the rotating substrate platen.

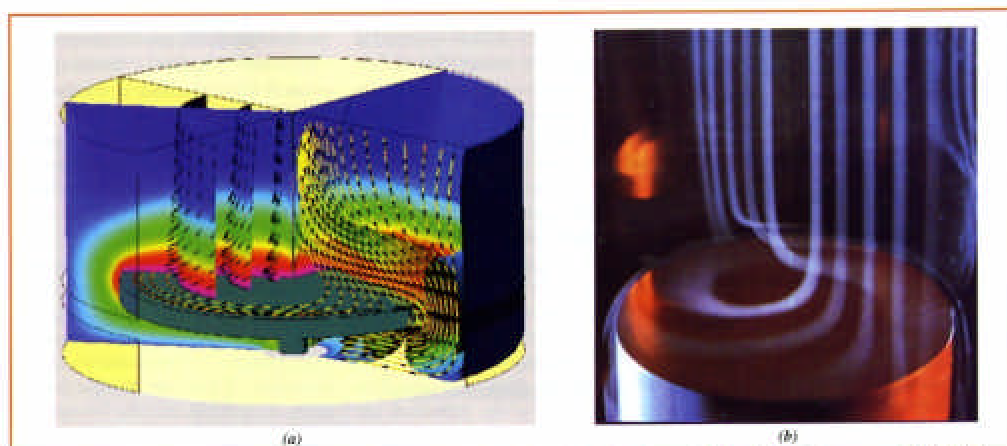


Figure 4. Gas flow patterns near the surface of a high speed rotating disk. **(a)** Results of numerical simulation of a commercial MOCVD performed at SML. **(b)** Actual visualization using reactive vapors, performed in a research reactor by Sandia National Laboratory. Photograph courtesy of Sandia National Laboratory.

Precursor Delivery System

The basic requirement for the precursor delivery system is to deliver the process gas mixture to the MOCVD reactor, with a molar composition and delivery rate that is predictable and controllable. **Figure 5** shows a liquid precursor "bubbler", which is one of the basic vaporization sources commonly used in MOCVD. A carrier gas is typically used to facilitate transfer of precursor vapor from the bubbler to the MOCVD reactor. The bubbler is typically placed in some type of temperature control apparatus (heating or cooling) to establish a specific vapor pressure of the precursor. Since equilibrium vapor pressures are exponentially dependent on temperature, precise temperature control is required.

The evaporation rate of a precursor material depends functionally on its surface area and on the saturation of the adjacent vapor. We can predict the molar flow rate of precursor vapor when a carrier gas is used, starting with the familiar gas law equations:

$$P_B = P_P + P_C \qquad P_P = \frac{N_P}{(N_C + N_P)}$$

$$P_C = \frac{N_C}{(N_C + N_P)}$$

in which;

N_P, N_C = the molar flow rates of the precursor and the carrier gas respectively.

P_P, P_C = the partial pressures of the precursor and the carrier gas respectively within the bubbler.

P_B = the total gas pressure within the bubbler.

These equations can be combined to predict the molar flow rate of precursor vapor (N_P) in terms of known system parameters, as;

$$N_P = N_C * \frac{P_P}{(P_B - P_P)} \qquad (1)$$

in which;

N_C = the known molar flow rate of the carrier gas, which is established by a mass flow controller.

P_B = the total gas pressure within the bubbler, which is measured by a pressure transducer and controlled by a variable flow valve (either manually or in automatic feedback mode).

P_P = the partial pressure of the precursor, which is calculated using known constants for the precursor material and the known bubbler temperature.

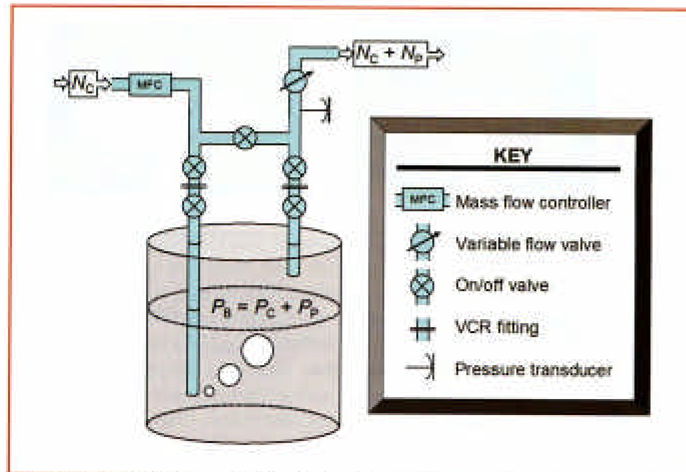


Figure 5. Basic bubbler source for liquid MOCVD precursors, showing provisions for carrier gas flow and bubbler pressure control.

The above equation assumes an ideal gas, with no reactions or condensation. It is also assumed that all partial pressures within the bubbler are at their equilibrium values, which means that the carrier gas flow rate is low enough such that near equilibrium conditions are achieved.

Control of precursor evaporation rate is relatively easy for liquids, but more difficult for solids. For metal organic precursors that are solid at the intended vaporization temperature, a arrangement similar to the bubbler shown in **Figure 5** can be used. However, using solid precursors presents several challenges in MOCVD. As a solid precursor mass evaporates, its size and shape will change. The surface area of the precursor mass will change as it evaporates, and thus the evaporation rate will drift with time. In addition, the flow path of carrier gas through a solid charge can change as the material evaporates. Often a preferential gas flow path or "microchannel" forms in the precursor charge. As less of the precursor surface is exposed to the carrier gas flow, equilibrium conditions are increasingly difficult to achieve in the source, and the molar delivery rate can change with time. For single component films, these difficulties can result in variation of the deposition rate with time. For multi-component films, variations in the film composition may result. For these reasons, it is generally preferable to use liquid precursor sources whenever possible.

Control of carrier gas flow rate NC and bubbler pressure PB are also important to the overall performance of an MOCVD bubbler. Improperly operated bubblers can result in precursor delivery rates that are unstable or not reproducible. The effect is illustrated in **Figure 6**, using a transparent bubbler. Bubbler conditions involving low carrier gas flow rate and/or high bubbler pressure cause pulses of precursor vapor, as each individual bubble bursts from the liquid. For the opposite extreme of conditions with high carrier gas flow rate and/or low bubbler pressure, excessively aggressive bubbling can occur. If liquid precursor is splashed into the downstream gas lines, it can cause unexpected surges of precursor vapor as the excess liquid evaporates in the gas lines. Either extreme of bubbler operating conditions can make control of film composition and thickness difficult.

While properly operated bubblers work well for single component precursors, they do not work for multi-component liquids. During evaporation of material from a bubbler, we are essentially doing a distillation. If there are multiple components in the liquid, then the lowest vapor pressure component will be removed at a higher rate, and the composition of the vapor flux will change with time. To

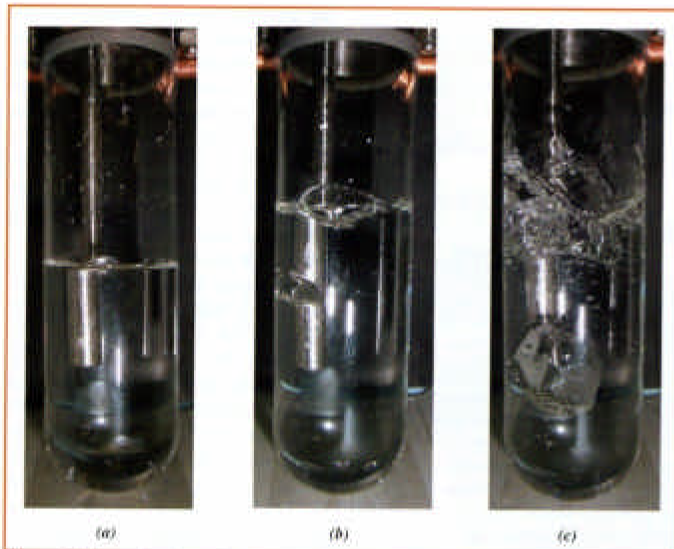


Figure 6. Effect of carrier gas flow rate on bubbler performance. The figures show a transparent bubbler at 100 Torr pressure, operating at carrier gas flow rates of: **(a)** 5.9 **(b)** 59 and **(c)** 590 standard cc/minute.

deposit multi-component oxide films by MOCVD, one of three strategies must be used, namely 1) use a metal organic precursor that contains multiple metal species, 2) use a separately controlled bubbler for each precursor, or 3) use a flash evaporator precursor source. While hetero-metal precursors do exist, they are as yet only available for a limited number of materials. In addition, these materials only produce the correct film stoichiometry in a narrow range of process conditions, and allow no flexibility in adjusting film composition. Using individual bubblers for each precursor is routinely done for both compound semiconductor materials and for complex oxides. Uniform films, abrupt interface or graded composition layers can be deposited, by adjusting the individual molar delivery rates according to equation (1) above. A degree of operator care is required to achieve the appropriate delivery rate for each material. This is best accomplished when liquid precursors with adequate vapor pressure are available for each material, which is not always the case.

For precursors that are solid at the intended vaporization temperature, or otherwise difficult to evaporate, the recommended approach is to use a flash evaporator. SMI's compact and efficient flash evaporator source is shown in **Figure 7**. Multiple metal organic compounds can be combined to form a precursor "cocktail"of precisely known molar ratio, which is then fed into the flash evaporator. For a properly operated flash evaporator, the composition and molar delivery rate of the vapor injected into the MOCVD reactor will be the same as that of the precursor cocktail. Proper operation of the flash evaporator means that all material is evaporated, and no accumulation occurs in the evaporator. Compositionally graded films can be prepared by feeding two or more cocktail streams into the flash evaporator with individually controlled rates. Use of a flash evaporator can provide several other significant advantages in MOCVD of complex oxides. Solid precursors can be flash evaporated by preparing a solution of the solid in a suitable solvent, avoiding the problems associated with solid source sublimation in MOCVD. Some metal organic precursors are susceptible to aging reactions (such as decomposition or polymerization) on prolonged exposure to high temperatures. For these materials, prolonged bubbler operation can lead to problems such as variations in molar

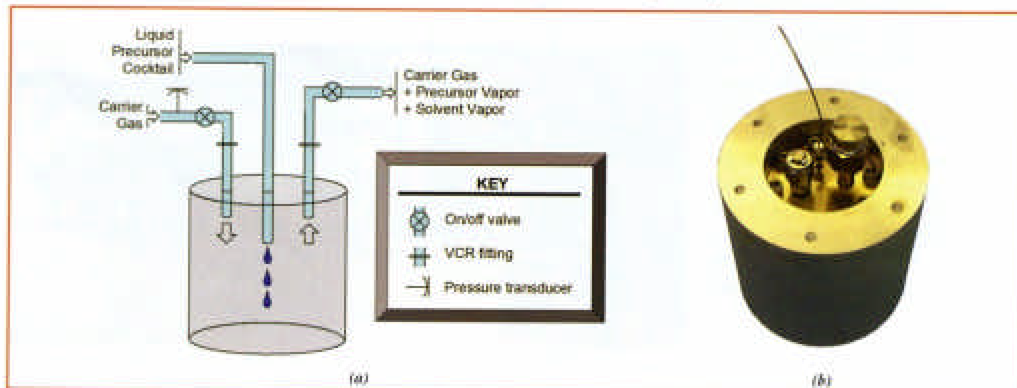


Figure 7. (a) Schematic illustration of a flash evaporator for vaporization of liquid MOCVD precursor solutions. **(b)** SMI's compact flash evaporator for MOCVD.

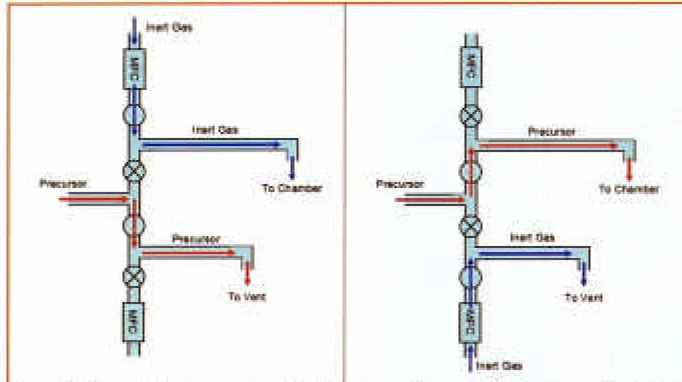
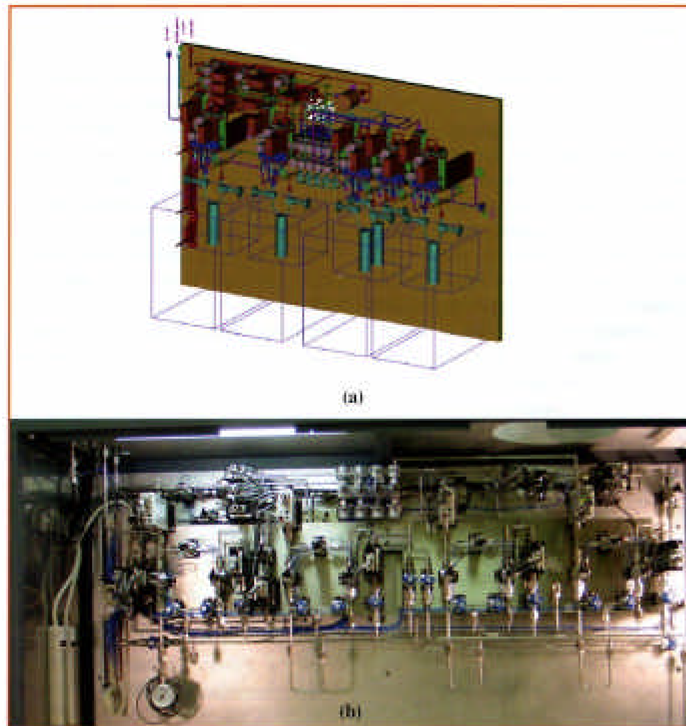


Figure 8. Schematic illustration of an MOCVD gas panel showing the arrangement for fast gas switching. The left figure shows the "Vent" configuration, in which precursor flow is directed to a vent while an inert gas flow is directed toward the MOCVD reactor chamber. The right figure shows the "Run" configuration, in which precursor flow is directed toward the MOCVD reactor while an inert gas flow is directed to a vent. Film deposition is initiated by quickly switching from the Vent to the Run configuration, and terminated by switching from Run to Vent. Maintaining good pressure balance in the lines prevents pressure surge or lag on gas switching, and helps ensure formation of abrupt interfaces.

delivery rate and clogging of source hardware. Flash evaporator delivery can provide more stable operation, since the precursor cocktail is initially held at ambient temperature. The precursor cocktail is only exposed to high temperature for a short time during actual vaporization in the flash evaporator.

A precursor delivery system or "gas panel" for the MOCVD reactor can be designed to include any combination of gas, liquid, solid or flash evaporator sources. The gas panel needs to be a well engineered system, which meets all requirements of the process and the device being built. Particular challenges are encountered when building devices that require abrupt interfaces between deposited layers. Such processes require the use of a fast gas switching arrangement, such as that shown in **Figure 8.** This gas panel configuration allows the operator to establish a stable precursor flow which is initially directed to a vent line. At the same time, an inert gas flow is sent to the MOCVD chamber and the substrate is maintained at the intended deposition temperature. Layer growth is initiated by reversing these flows to the "Run" configuration, as shown in **Figure 8**. Layer growth is terminated by switching the gas flows back to the "Vent" configuration. The vent line and chamber line must be continually maintained at the same pressure, so that no flow surge or lag occurs on gas switching. This ensures that there is minimal time lag between operation of the hardware and actual switching of the process gas flows. For best control of layer thickness, it is also important to keep the gas line volume between the chamber and the switching manifold as small as possible.

Figure 9 shows an example of a gas panel designed to provide safe, efficient and reproducible delivery of MOCVD precursors for complex oxide thin film deposition. The gas panel provides for optimum operation of multiple precursor sources, including all provisions for carrier gas flow and for fast gas switching. The design also allows the end-user to isolate, evacuate and purge any component of the gas panel, and facilitates easy changing of precursors and purging of gas lines after changes. To accomplish these goals, gas



(a)

(b)

Figure 9. Complete MOCVD gas panels are configured for the needs of the deposition process and the device being fabricated. This example shows a gas panel configured for four independent liquid source bubblers. **(a)** CAD drawing of the gas panel. **(b)** Photograph of commercial MOCVD gas panel.

pressure needs to be measured and gas flows need to be controlled at numerous points in the precursor delivery system.

Process Control

Many parameters need to be accurately monitored and controlled in MOCVD of complex oxides. Temperature, pressure and flow rate need to be measured and controlled at numerous locations in the precursor delivery system. Process parameters including substrate temperature, chamber pressure and substrate rotation speed must also be controlled. Inputs from various external sources, such as in-situ monitors, must be processed and decisions made based on the results. The rotating disk MOCVD system uses SMI's Advanced computer control system [13] to fulfill all of these functions. The system provides for control of all process and hardware parameters, either manually, or in full automatic mode according to user supplied recipes. The control system provides for simplified operation of the MOCVD system, as well as for greater reproducibility of the deposition process. The system also provides for data logging and trend analysis, as well as communication to external computers and networks.

High Volume Production Systems

The complex oxide MOCVD system can be readily scaled up to large wafer sizes or for batch operation. Substrate platens can be designed for single wafer sizes through 300 mm diameter, or for multiple smaller wafers on one large platen. The later arrangement is advantageous for substrate wafers that are only available in small sizes. Load-locks can be added for improved chamber cleanliness and higher throughput. Load-locks allow for faster wafer cycling, since shorter pump-down times and shorter wafer cool-down times can be used. The complex oxide MOCVD system can also be supplied in a cluster arrangement, as shown in **Figure 10**. The cluster tool can provide multiple process capabilities on the same platform (such as etching or rapid thermal processing) for greater functionality. Conversely, the cluster tool can be configured with multiple MOCVD

Figure 10. The rotating disk MOCVD reactor mounted in a cluster tool arrangement, along with an etch module and cassette-to-cassette load-locks.

Figure 11. A complete packaged MOCVD system for complex oxide thin films; including the reactor, gas panel, control system and all accessories, packaged in a single functional cabinet.

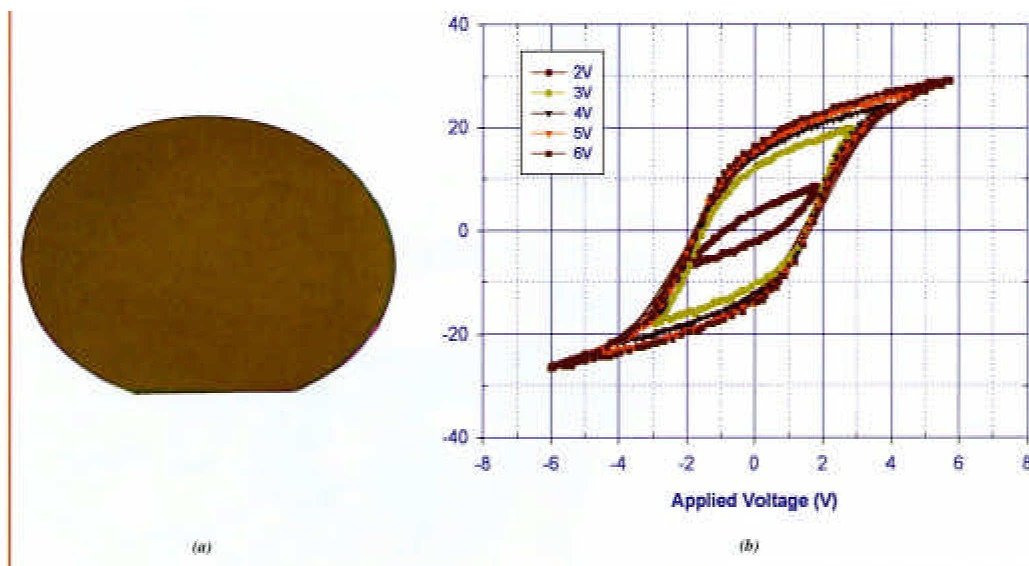


Figure 12. **(a)** Example of a $Pb(Zr_xTi_{1-x})O_3$ thin film uniformly deposited on a six inch wafer in a rotating disk MOCVD reactor. **(b)** Measured ferroelectric data for MOCVD deposited $Pb(Zr_xTi_{1-x})O_3$ thin film.

modules on the same platform, for increased throughput. Complete systems (either single module or cluster) are packaged together with the MOCVD reactor, the gas panel, the control system, power supplies, vacuum pumps and safety systems, all in one functional cabinet, as shown in **Figure 11**.

Conclusions

An MOCVD system has been designed specifically to meet the challenges of complex oxide thin film deposition. The system has been used to produce a wide variety of complex oxide thin films [14], including all of the materials listed in **Table I**. Of particular interest are the ferroelectric oxide materials, such as lead zirconium titanate (PZT). **Figure 12** shows a uniform PZT film deposited on a six inch wafer by MOCVD, and the measured ferroelectric properties. Another material of considerable commercial interest is zinc oxide. With proper doping or alloying, zinc oxide can function as a transparent conductor, semiconductor or electro-optical material. The complex oxide MOCVD system provides the required composition control to make zinc oxide thin films for all of these applications [15]. Many other multi-component oxide materials have been investigated, including piezoelectric, pyroelectric and superconducting materials. These materials find applications in data storage, displays, telecommunications, sensors, MEMS and power distribution components, as well as many other current and future products. Research and production versions of the complex oxide MOCVD system are now available to meet the growing demands for these advanced materials.

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Nick M. Shrockey has over 20 years of experience in thin film deposition and semiconductor device processing. He has held R&D positions at Axcelis Technologies, Eaton Corporation and Balzers High Vacuum Systems and Components. He joined Structured Materials Industries in 2002, where he leads research programs on very low absorption optical coatings, thin film waveguides, photonic crystals and thermophotovoltaic energy conversion devices. Dr. Shrockey's education includes a B.S. in Metallurgical Engineering from the University of Cincinnati and a Ph.D. in Materials Science and Engineering from Northwestern University. He has authored or co-authored 18 technical papers and conference presentations, holds one patent and has two patents pending. He can be reached at sbrockey@structuredmaterials.com.

Joseph D. Cuchiaro is Vice President of Business Development at SMI. Mr. Cuchiaro contributes to the organization over 15 years of experience in oxide materials development, IC integration and product commercialization. He joined SMI in October 1999 to lead technology expansion for oxide material integration, device development and IC oxide system development. Mr. Cuchiaro has published approximately 25 technical papers, been awarded 29 patents and submitted over 20 disclosures that are pending award in the field of thin film oxides. Mr. Cuchiaro performed his MSEE and BS Physics and Energy Science studies at the University of Colorado and is an Organizer in the Electrochemical Society "Integrated Ferroelectrics for Memory Applications" Symposium as well as a consultant to Celis Semiconductor.

Brent H. Hoerman is a materials scientist with extensive experience in deposition, processing and characterization of bulk and thin film materials for electrical and optical device applications. His education includes BS degrees in physics and mathematics from the University of Wisconsin – Stevens Point and a Ph.D. in Materials Science and Engineering from Northwestern University. Dr. Hoerman's research has resulted in over 30 technical publications and presentations. He is a member of the Materials Research Society and of the American Physical Society. Dr. Hoerman recently joined SMI, adding expertise in electronic and photonic materials and leading materials and device development efforts.

L. Gary Provost joined SMI in January of 1998 to lead several projects in the area of oxide thin films produced by MOCVD. Prior to joining the company, Mr. Provost was Project Engineer with Kulite Semiconductor Products Inc., Leonia NJ, where he worked on developing Si, SiC, and Diamond High Temperature Dielectrically Isolated Piezoresistive Pressure Transducers. Mr. Provost obtained his Bachelors of Science in Electrical Engineering Technology from Northeastern University, Boston Massachusetts in June 1986. He has several publications and one patent pending. He is a member of the Tau Alpha Pi National Honor Society as well as a member of IEEE and the American Vacuum Society.