Liquid or Solid?

Navigating Precursor Selection for Next-Generation Semiconductor Deposition

White paper

As semiconductor device architectures continue to evolve, the materials used to build them are evolving as well. Advanced logic and memory technologies require increasingly complex deposition processes, tighter impurity control, and improved film performance. These demands are driving manufacturers to re-evaluate key aspects of process chemistry including the physical format of chemical vapor deposition (CVD) and atomic layer deposition (ALD) precursors.

Deposition precursors are high-purity chemicals used to form thin films on silicon wafers through processes such as ALD and CVD. While liquid precursors have historically been the industry's default, selecting between liquid and solid formats is becoming an increasingly strategic decision.

As device geometries shrink and new materials are introduced, the limitations of traditional precursor chemistries are becoming more pronounced. Film performance requirements have tightened as films become thinner, aspect ratio becomes higher, and interfaces increasingly dominate behavior, while impurity budgets continue to shrink. Deposition reactions must also be more precise and predictable than ever before.

As a result, precursor format selection is evolving from a routine chemistry choice into a broader materials engineering decision. In many cases, liquid precursors remain the optimal solution. In others, emerging materials, such as molybdenum, are demonstrating that solid precursors become better choices to enable the performance required for next-generation devices.

Understanding when and why to use each format is therefore becoming a critical capability for semiconductor manufacturers. Entegris supports this decision-making process by combining deep chemistry expertise with advanced delivery technologies enabling optimal precursor selection regardless of physical form.

THE TECHNOLOGY DRIVERS BEHIND PRECURSOR FORMAT DECISIONS

The growing importance of precursor format selection is rooted in the rapid evolution of semiconductor devices. As advanced logic and memory technologies scale, deposition processes must deliver films with increasingly demanding electrical and structural properties.

One key driver is the shrinking tolerance for impurities within deposited films. Many liquid precursors used in semiconductor manufacturing are organometallic compounds. While effective for delivering metal atoms, these molecules often contain carbon, nitrogen, or oxygen, elements that can be incorporated into the film.

At earlier technology nodes, these levels of contamination were often acceptable. As device dimensions shrink and film thickness decreases, however, even small amount of trace impurities can significantly impact performance. Carbon incorporation, for example, can increase resistivity in conductive films and alter dielectric properties in insulating layers. As a result, precursor chemistry must be carefully engineered to minimize unwanted elements.

The interaction between precursor chemistry and surface reactions is also increasingly critical. Deposition is fundamentally a surface-driven process, and the structure of a precursor molecule directly influences its reactivity with the wafer surface. Ligand design, reaction pathways, and decomposition behavior all play a defining role in final film quality.

LIQUID-FIRST DECISION FRAMEWORK

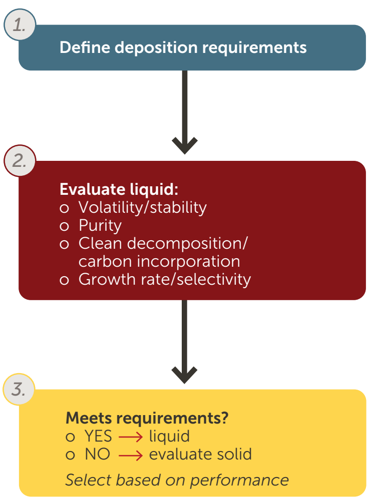
Liquid precursors remain the starting point for most deposition processes. They are generally easier to scale, purify, and analyze, with well-established distillation methods enabling consistent production of high-purity materials. Their mature supply chains and compatibility with existing tool infrastructure further reinforce their role as the default option.

As a result, precursor evaluation typically follows a "liquid-first" approach:

- **Evaluate** film performance, purity, and process stability against device requirements. If targets are met, proceed with liquid qualification.
- **Identify** chemistry or performance limitations (e.g., impurity incorporation, insufficient volatility, or stability constraints). If acceptable, advance toward production; if not, evaluate alternatives.
- **Expand** to solid precursors when liquid chemistries cannot meet requirements. If targets are achieved, proceed with solid delivery integration.

Importantly, solid precursors are not a fallback, they represent a deliberate engineering solution when liquid chemistries cannot meet performance requirements. As device demands increase, solid precursors are becoming an increasingly important option for enabling higher film purity and alternative reaction pathways.

Precursor Selection Decision Flow



ENGINEERING TRADEOFFS

Comparisons between liquid and solid precursors are often framed as a competition between two formats. In practice, the more relevant question is which format best supports a specific application.

Liquid precursors offer clear advantages in scalability and process integration. Their mature supply chains and well-understood handling methods make them the most efficient and practical option when they can meet performance requirements.

Solid precursors, however, can provide distinct benefits when chemical or reaction constraints limit liquid performance. In many cases, solid precursor molecules enable alternative ligand structures that reduce impurity incorporation or support different surface reaction mechanisms.

Historically, one of the primary challenges associated with solids has been delivery. Maintaining stable vapor flux from a solid source requires precise thermal management and system design. Delivery lines must be trace-heated to prevent condensation, and systems must maintain consistent vapor pressure. Additionally, many solid precursors are highly corrosive at vaporization temperatures, introducing additional design challenges.

Advances in delivery technologies have significantly mitigated these challenges. Modern solid precursor delivery systems use engineered evaporation platforms to maximize surface area and maintain stable precursor flux, enabling the vapor delivery rates required for high-volume semiconductor manufacturing. (See Figure 1)

Figure 1: Engineering Tradeoff Matrix

DIMENSION	LIQUID PRECURSORS	SOLID PRECURSORS
Supply chain maturity	High	Emerging → Advanced
Purification scalability	Strong	Material-dependent
Film purity	Chemistry-limited, often carbon	Often higher ceiling, different impurity profile
Delivery complexity	Lower	Higher (managed by design)
Fit for advanced nodes	Conditional	Increasingly critical
Cost Of Ownership	Lower system complexity, but may require compromises	Higher delivery complexity, but potential performance yield gains

While Figure 1 summarizes the strategic tradeoffs between liquid and solid precursors, Figure 2 shows how those differences translate into the practical delivery pathway from source package to process chamber

COST OF OWNERSHIP CONSIDERATIONS

Cost of ownership (COO) is often assumed to favor liquid precursors due to their simpler delivery systems and established infrastructure. While liquids can offer advantages in terms of system integration and operational familiarity, this perspective does not fully capture the total process impact.

In advanced applications, precursor selection directly influences film purity, defectivity, and process stability, all of which can affect yield and downstream process complexity. In cases where liquid precursors introduce impurities or require additional process optimization, apparent system-level cost advantages may be offset by performance-related tradeoffs.

Solid precursors, while sometimes requiring more sophisticated delivery systems, can enable improved film quality or alternative chemistries that are not achievable in liquid form. When evaluated at the process and device level, this can translate into meaningful benefits in yield, performance consistency, and overall manufacturing efficiency.

As a result, COO comparisons should be evaluated holistically, considering not only delivery infrastructure but also the impact of precursor chemistry on process performance and device outcomes.

CORRECTING COMMON MARKET MISCONCEPTIONS

Despite their growing importance, several misconceptions continue to influence how liquid and solid precursors are perceived:

Myth 1: Solid precursors are inherently inferior to liquid precursors.

In reality, precursor performance is determined primarily by chemistry rather than physical format. For some materials, the most effective precursor molecules exist in solid form. In several more recent new materials being adopted by advanced nodes, solid precursors perform superior to liquid ones.

Myth 2: Liquids are always easier to use.

While liquid delivery infrastructure is more mature, certain chemistries cannot deliver the required performance in liquid form. As device requirements evolve, these limitations are becoming more apparent. After more than 15 years of industry implementation, solids are showing maturity close to the same level vs. Liquids.

Myth 3: Suppliers focused on solid precursors lack competitive liquid offerings.

Leading materials suppliers maintain robust portfolios across both liquid and solid precursor categories. The objective is not to favor one format, but to identify the chemistry that best enables performance.

These misconceptions are significant because they can lead teams to prioritize format familiarity over optimal material selection. A solution centric approach evaluating liquid options first while maintaining flexibility to transition to solids ensures that precursor decisions are driven by performance rather than bias.

MOLYBDENUM: A SOLID EXAMPLE

Molybdenum is emerging as a leading example of a material where solid precursor delivery is not only viable, but necessary. Its electrical properties make it attractive for advanced device architectures, yet developing effective liquid molybdenum precursors has proven challenging due to carbon incorporation.

As with many liquid metal precursors, carbon contamination can degrade electrical performance. In advanced nodes, even trace levels can have measurable impacts.

The purity advantages of certain solid precursors are rooted in their underlying chemistry. Many liquid metal precursors rely on organometallic ligands that inherently contain carbon or other elements, which can be incorporated into the film during deposition. In contrast, some solid precursor chemistries, such as halide- or oxide-based systems, offer alternative reaction pathways with lower intrinsic carbon content. This can reduce impurity incorporation and enable higher film purity, particularly for materials such as molybdenum where even small amounts of carbon can degrade electrical performance.

Alternative chemistries based on halides or oxides offer improved reaction pathways for molybdenum deposition. These chemistries are typically delivered as solids rather than liquids.

The industry's adoption of solid molybdenum precursors has accelerated the development of delivery technologies capable of supporting large-scale manufacturing marking an important inflection point. As more materials follow similar trajectories, solid precursor technologies are expected to play an increasingly important role.

ENTEGRIS' LEADING ROLE

Entegris combines deep expertise in liquid precursor chemistry with advanced solid precursor delivery technologies, enabling comprehensive support from early-stage materials evaluation through high-volume manufacturing integration.

The company's liquid precursor portfolio reflects long-term investment in purification, analytical characterization, and scalable production. These chemistries remain foundational to semiconductor deposition and continue to evolve through ongoing collaboration with OEMs and device manufacturers.

In solid precursor technologies, Entegris has developed advanced evaporation platforms, container designs, and delivery systems to ensure consistent precursor flux in modern deposition environments. These capabilities are expanding the practical use of solids from specialized applications into broader manufacturing contexts.

This dual capability is particularly valuable as the industry explores emerging materials such as molybdenum and other next-generation metals. In these cases, success depends not only on identifying a viable precursor molecule, but also on delivering it safely, consistently, and efficiently within a fab environment.

By integrating materials science expertise with delivery infrastructure, Entegris works collaboratively with OEMs and device manufacturers to evaluate both liquid and solid options supporting optimal precursor selection for each application.

SSDC 1000 is a fully automated delivery system for solid precursors.

The ProE-Vap® Delivery System is designed for solid precursors.

The Unichem™ 3000 series is designed for liquid chemical delivery systems.

CONCLUSION

The semiconductor industry is entering a phase where materials decisions are as critical as device architecture. As technologies continue to scale, the chemistry used to create deposited films will play an increasingly central role in determining device performance and yield.

Precursor selection is no longer a routine materials choice, it is a strategic decision that directly impacts film purity, electrical performance, and process stability.

While liquid precursors will remain the starting point for most applications, solid precursors are becoming essential where performance requirements exceed the limits of conventional chemistries.

By combining expertise in both precursor chemistry and delivery systems, Entegris helps semiconductor manufacturers navigate this complexity ensuring that the optimal precursor format is selected for each application and enabling the next generation of semiconductor innovation.

Figure 2: Liquid and Solid Precursor Delivery Pathways

DELIVERY STEP	LIQUID PATH	SOLID PATH	DELIVERY IMPACT
Source package	Standard ampoule or liquid container – Unichem™ 3000 series*	Engineered vessel for controlled vapor generation – ProE-Vap® Delivery System and SSDC 1000*	Defines access, heating, replacement, and integration.
Vapor generation	Vapor draw, bubbling, or liquid injection.	Sublimation or evaporation from an engineered platform.	Determines usable vapor consistency.
Temperature control	Established controls for containers, vaporizers, and lines.	Tightly controlled source, vessel, and line temperatures.	Maintains vapor pressure and stable delivery.
Vapor transport	Mature flow paths and delivery-line designs.	Trace-heated lines and condensation control.	Preserves vapor phase to the chamber.
Dose/flux stability	Predictable when properties match process needs.	Depends on surface exposure, heat, and evaporation design.	Supports repeatable dose and film uniformity.
Tool integration	Often fits existing liquid-ready tool infrastructure.	May require added modules, heating, or vessel-specific design.	Balances integration effort with chemistry benefit.
Operational control	Familiar handling, flow control, and monitoring.	Requires careful heating, loading, compatibility, and stability controls.	Converts chemistry advantage into reliable fab performance.

**Associated Entegris products*

ABOUT ENTEGRIS

Entegris is a world-class supplier of advanced materials and process solutions for the semiconductor and other high-tech industries. Entegris is ISO 9001 certified and has manufacturing, customer service, and/or research facilities in the United States, Canada, China, France, Germany, Israel, Japan, Malaysia, Singapore, South Korea, and Taiwan. Additional information can be found at entegris.com.

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