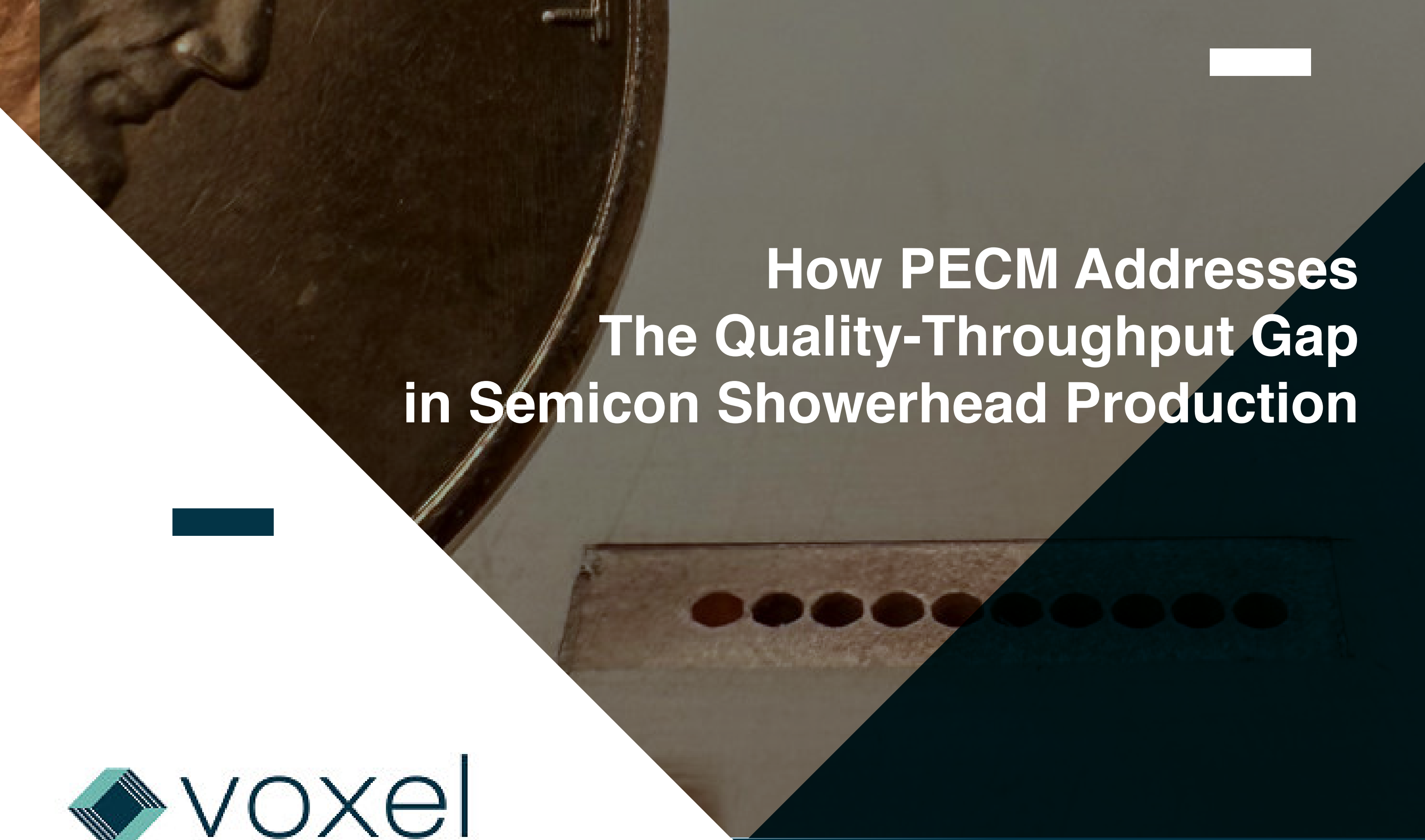


How PECM Addresses The Quality-Throughput Gap in Semicon Showerhead Production

voxel

Semiconductor manufacturing is increasingly defined by its invisible geometries….

…Such as the thermal microchannels routed beneath high-power devices, the internal flow paths inside gas-handling hardware, and the sub-millimeter features that regulate heat, pressure and chemical purity at scale.

1

PECM is ideal for **semiconductor gas and fluid delivery components** where internal surface quality, feature consistency, and defect avoidance are critical.

2

PECM supports components that demand tight geometric control, repeatable features, and non-contact material removal, such as for **wafer processing equipment** and **tooling.**

3

PECM's capabilities are adept for **semiconductor thermal infrastructure** that relies on internal channels, microfeatures, or thin-walled geometries to manage heat efficiently.

520 Hinton Pond Road, STE 128,
Knightdale, NC 27545

info@voxelinnovations.com

984-464-0701

www.voxelinnovations.com

Layer 1: **Excecutive Summary**

The Precision Challenge at **Sub-nm Nodes**

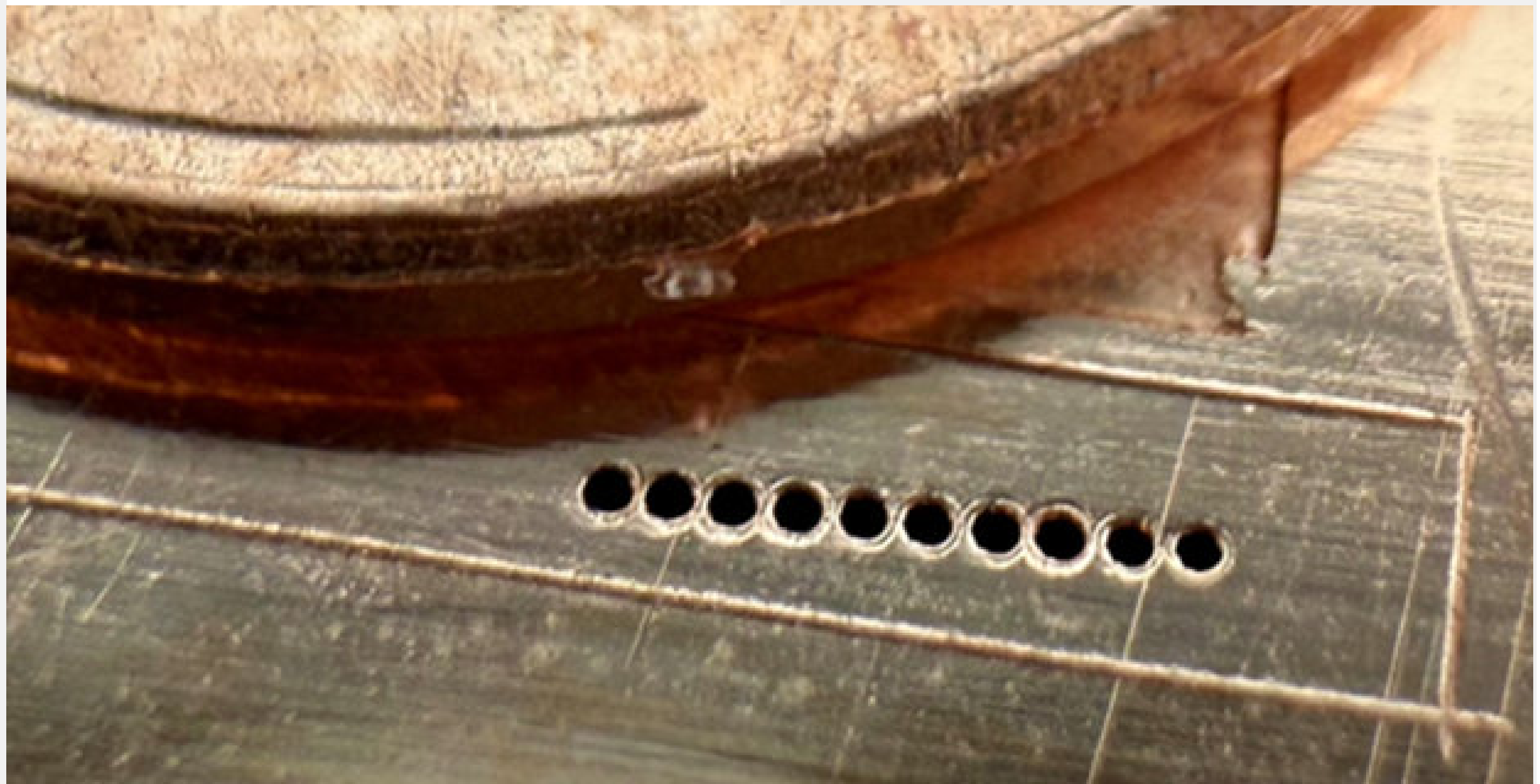
The semiconductor industry's transition to gate-all-around (GAA) transistor architectures at 2nm and below has compressed the tolerance envelope for every component in the fabrication process chain. Among the most affected are the gas distribution plates and showerheads inside chemical vapor deposition (CVD), atomic layer deposition (ALD), and plasma etch tools. These components -- perforated with thousands to tens of thousands of precision micro-orifices arranged in multi-zone concentric patterns -- are the primary mechanism by which process gases are distributed uniformly across 300mm wafer surfaces. At sub-2nm nodes, the relationship between showerhead orifice quality and within-wafer process uniformity is direct and unforgiving: variations of even a few microns in hole diameter, wall roughness exceeding 0.2 um Ra, or the presence of recast material inside orifices translate to measurable non-uniformity in film thickness or etch rate across the wafer.

The **Yield Consistency Gap**

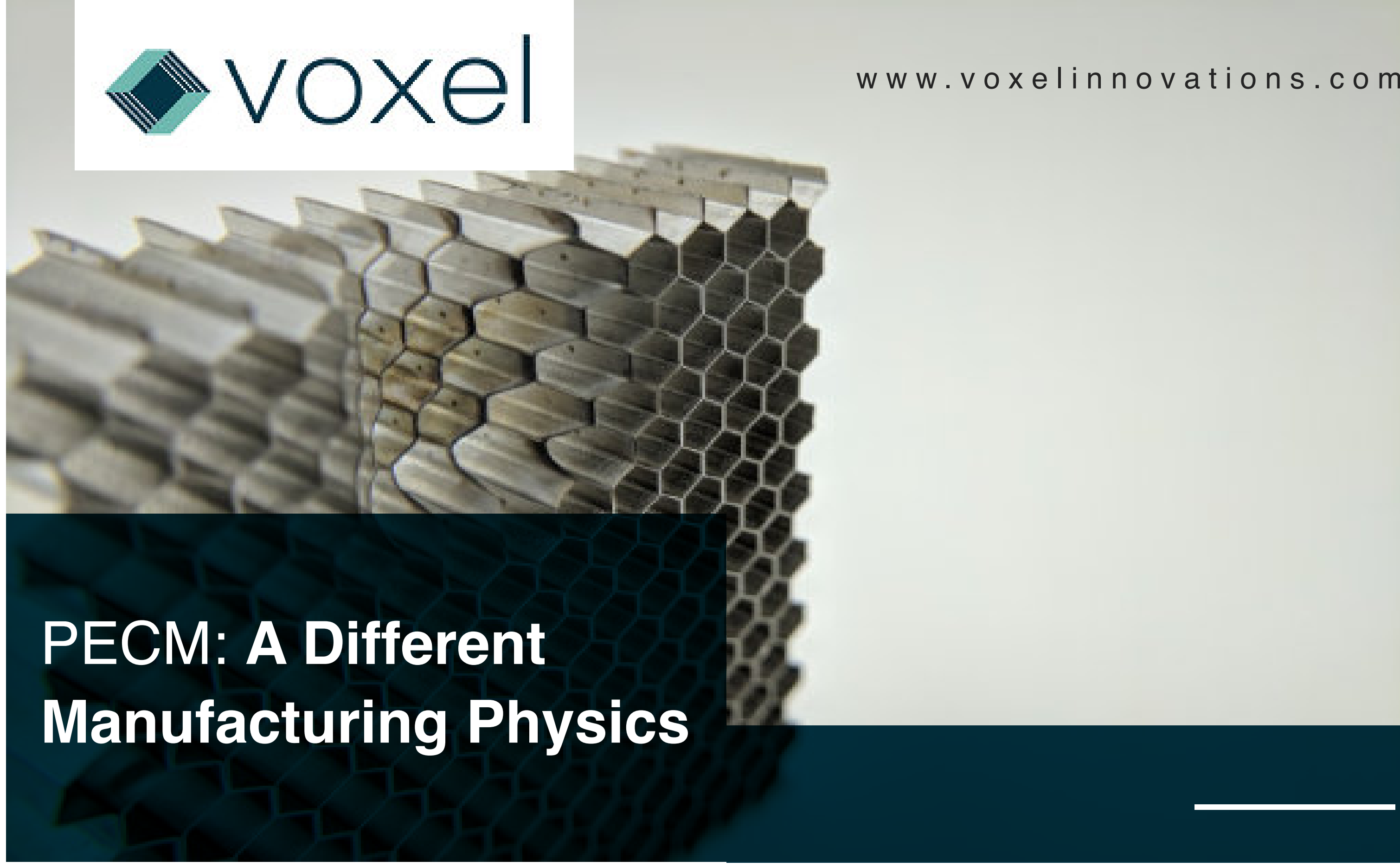
Beyond the tolerance challenge at future nodes, semiconductor equipment manufacturers face a more immediate quality concern: yield consistency at current production specifications. Showerhead components manufactured via thermal methods exhibit hole-to-hole variation that increases across production runs as electrodes wear. This progressive degradation means that even when nominal specifications are met, yield losses accumulate -- and supply constraints often force acceptance of components that meet print but underperform in process. A manufacturing method with inherently stable output addresses this yield gap directly.

The **Manufacturing Gap**

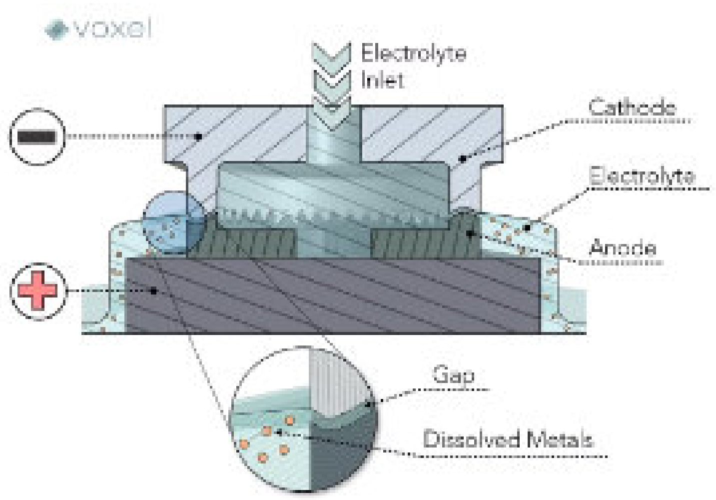
The dominant manufacturing method for these precision orifice arrays -- Electrical Discharge Machining (EDM) -- has served the semiconductor equipment industry for decades. EDM processes any conductive material, achieves reasonable hole geometries, and benefits from an extensive qualification infrastructure across the supply chain. However, EDM operates through controlled electrical spark discharges that melt and vaporize workpiece material, and this thermal mechanism introduces fundamental limitations that become increasingly problematic as tolerance specifications tighten. Every EDM-drilled hole develops a recast layer of re-solidified material on its inner wall. The surrounding material contains a heat-affected zone with altered microstructure. EDM electrodes wear progressively during use, meaning the first hole drilled on a 12-inch showerhead plate is geometrically different from the last. A single plate with tens of thousands of holes requires more than 20 hours of machining time and 10 or more electrode changes, each introducing potential alignment error. After machining, acid washing is required to remove recast layers -- an additional process step that introduces contamination risk and cycle time.



www.voxelinnovations.com



PECM: **A Different Manufacturing Physics**



Pulsed Electrochemical Machining (PECM) removes material through an entirely different mechanism: controlled anodic dissolution. A shaped cathode tool and the workpiece are positioned within a flowing electrolyte solution. Pulsed electrical current dissolves metal atoms from the workpiece surface according to Faraday's law of electrolysis. There is no melting, no spark discharge, no thermal energy input. The cathode does not contact the workpiece, and cathode wear is substantially lower and more predictable than EDM electrode wear.

The implications for showerhead manufacturing are direct. PECM produces zero recast layer and zero heat-affected zone -- the as-machined surface is pristine parent material. Cathode wear is significantly reduced compared to EDM electrode wear, so the geometry of the fifty-thousandth orifice closely matches the first, with high hole-to-hole consistency enabled by the reduced-wear cathode.

Specific tolerances are geometry-dependent and validated during DFM engagement. Surface finishes below 0.4um Ra, with results down to 0.1um Ra achievable, are produced in a single operation– well beyond the sub-0.2um Ra wall roughness specifications required at advanced nodes. No acid washing, deburring or secondary finishing is required.

www.voxelinnovations.com

Key Takeaways

1.

Substantially reduced tool wear addresses a significant source of hole-to-hole variation in showerhead manufacturing. Because the PECM cathode experiences significantly less wear than EDM electrodes, orifice geometry remains highly consistent across multi-thousand-hole arrays. This directly supports the within-wafer gas uniformity that determines process performance at advanced nodes.

2.

Elimination of recast layers and heat-affected zones removes a significant contamination concern in ultra-high purity process environments. Recast material can shed under thermal cycling or plasma exposure. PECM's electrochemical dissolution mechanism makes recast formation physically impossible.

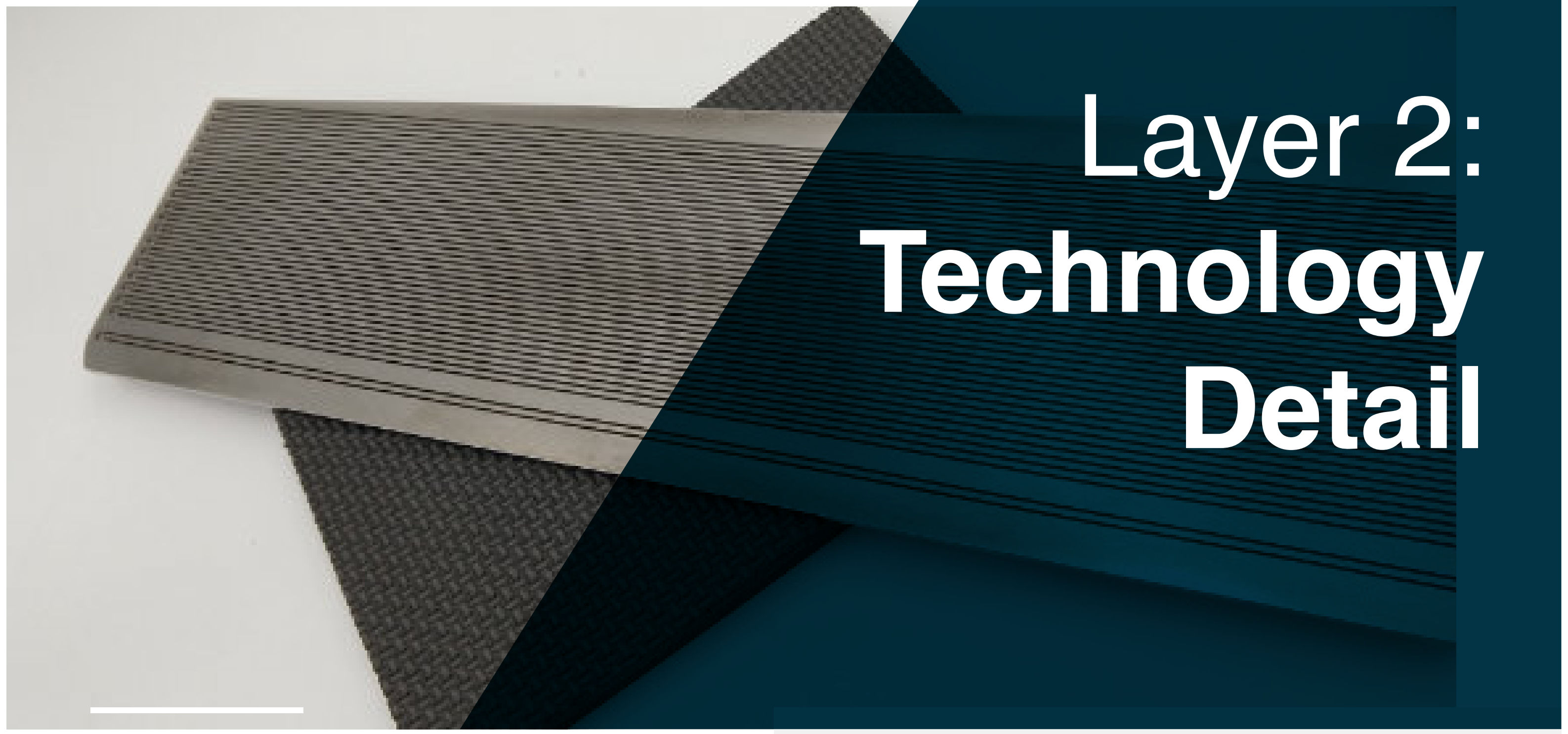
3.

PECM processes any conductive material regardless of hardness, at comparable speed and with consistent geometric fidelity. Aluminum, nickel alloys (Inconel, Hastelloy), stainless steel, and molybdenum-based alloys -- the full palette of materials used in semiconductor showerheads and gas distribution components -- are machined with consistent geometric fidelity. Material hardness, which significantly constrains mechanical drilling and accelerates EDM electrode wear, is irrelevant to electrochemical dissolution. Additionally, PECM's multi-featured cathode tooling addresses hundreds to thousands of features simultaneously -- a parallel processing model that offers fundamentally different throughput economics compared to serial methods like EDM and laser drilling.

4.

PECM's stable cathode mechanism supports yield consistency at current production specifications. While future nodes will demand tighter tolerances, the immediate value proposition is predictable, repeatable output that reduces yield losses from manufacturing-induced variation in today's production.

voxel



Layer 2: **Technology Detail**

The **Gas Uniformity Imperative**

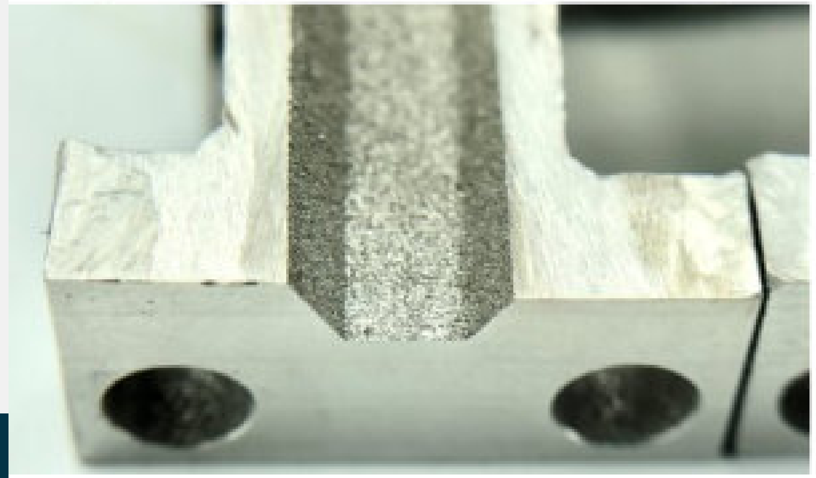
In semiconductor deposition and etch processes, the showerhead is the last component between the gas delivery system and the wafer surface. Its function is to transform a bulk gas supply into a spatially uniform flux of reactive species across the full diameter of a 300mm wafer. The physics are straightforward: gas enters a plenum on the back side of the showerhead plate and exits through an array of precision orifices into the process chamber. Each orifice acts as a flow restriction, and the collective behavior of thousands of orifices determines the spatial distribution of gas arriving at the wafer.

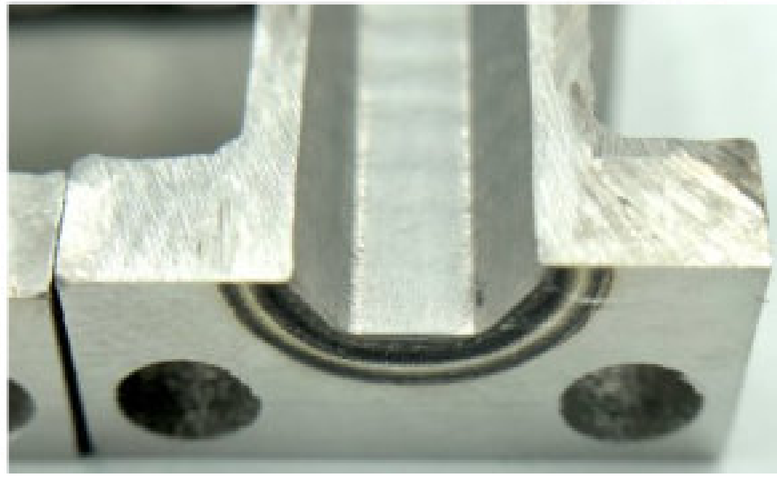
This creates a direct causal chain from orifice quality to wafer process quality. Hole diameter uniformity determines gas flow distribution across the wafer -- variations cause localized over-deposition or under-etch. Inner wall roughness affects flow resistance per hole, where rough walls create turbulence and inconsistent flow rates. Hole taper introduces directional bias in gas jet trajectory. Burrs at hole exits disrupt laminar flow and, critically, become particle sources under plasma bombardment. Recast layers from thermal machining processes narrow the effective hole diameter, alter flow characteristics, and create contamination risk as the material degrades under process conditions.

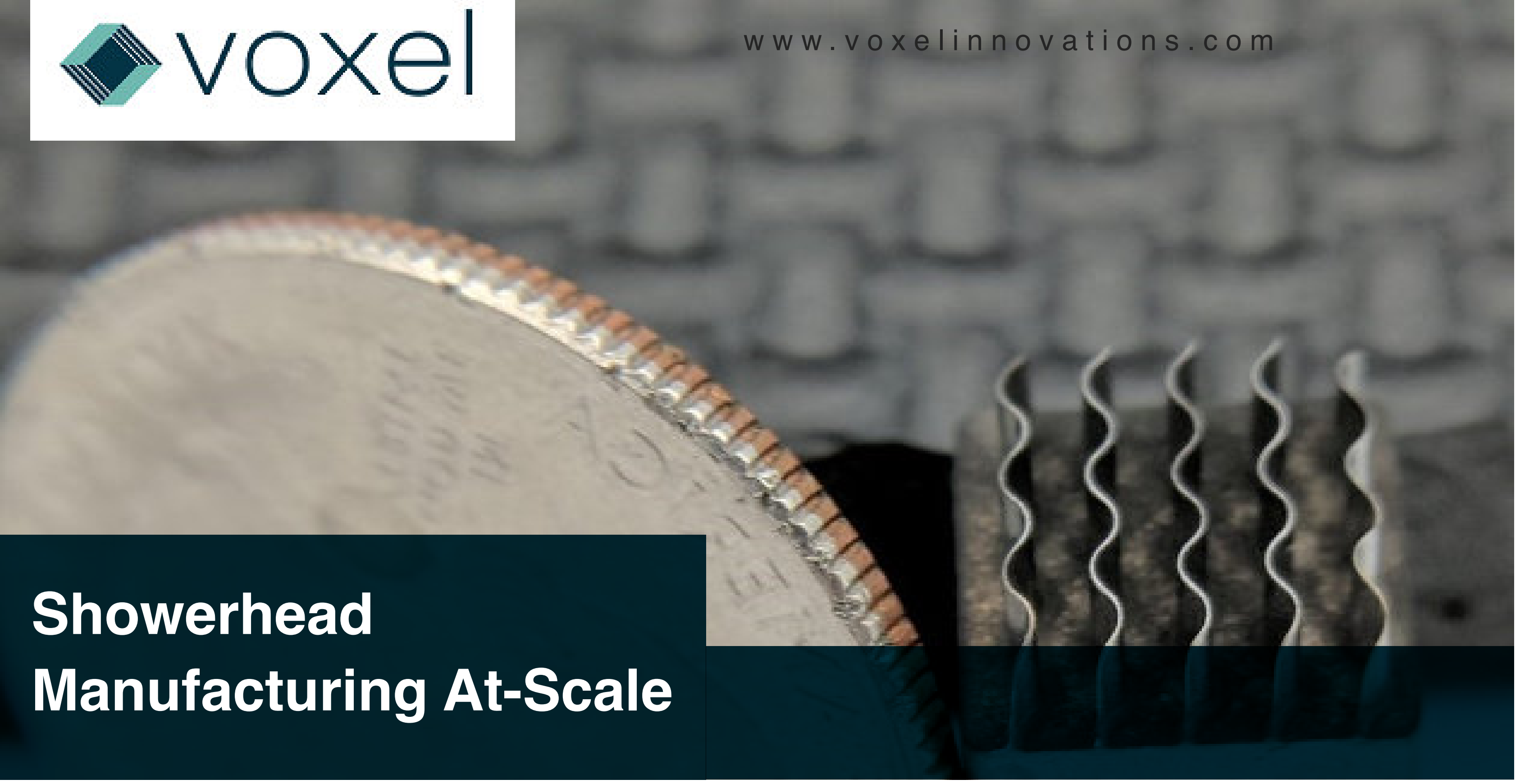
At mature technology nodes, these effects were manageable within the broader process window. At sub-2nm GAA nodes, the process window has narrowed to the point where showerhead orifice quality is a first-order determinant of within-wafer uniformity. Published patent literature from semiconductor equipment manufacturers confirms this: multi-zone showerhead designs with concentric hole patterns, independent gas plenums, and zone-specific orifice sizing have been developed precisely because uniform gas delivery at these dimensions requires manufacturing precision at the limit of current capability.

Modern showerhead architectures reflect this precision demand. Advanced designs incorporate dual-plate assemblies where a tuning plate with small orifice holes sits above a diffuser plate with larger apertures, with the alignment and size ratio between plates controlling flow resistance per zone. Chamfered hole exits minimize turbulence as gas jets enter the chamber. Multiple independent gas plenums allow different gas compositions or flow rates to be delivered to different zones of the wafer. Each of these design features requires manufacturing capability that can produce orifices with controlled geometry, consistent dimensions, and contamination-free surfaces across arrays of thousands to tens of thousands of holes per plate.

As process nodes continue to shrink and chamber architectures become more complex, the manufacturing precision required for these gas distribution components only increases. The ability to produce large arrays of micro-orifices with consistent geometry, clean internal surfaces, and minimal dimensional shift has therefore bcome a critical enabler of stable process performance at advanced semiconductor nodes.







Showerhead Manufacturing At-Scale

Five manufacturing methods are used for precision micro-orifice production in semiconductor showerheads. Each has distinct capabilities and limitations.

Electrical Discharge Machining (EDM) is the dominant incumbent. EDM removes material through controlled spark discharges between a shaped electrode and the workpiece, submerged in a dielectric fluid. For showerhead applications, EDM offers the ability to process any conductive material and has decades of established qualification data at semiconductor equipment OEMs.

EDM's limitations are inherent to its thermal mechanisms.

Recast layer formation: Every EDM-drilled hole develops a recast layer (typically 5-30 um thick) of re-solidified material on the inner wall. This recast is metallurgically distinct from the bulk material -- different grain structure, embedded dielectric breakdown products, and micro-cracks from rapid thermal cycling. In semiconductor process environments, recast material can flake under thermal cycling or plasma exposure, generating particulate contamination. Industry practice requires acid washing after EDM to remove recast layers, adding cycle time, cost, and secondary contamination risk.

Progressive electrode wear: EDM electrodes erode during use. Over a production run of tens of thousands of holes on a single 12-inch showerhead plate, this wear causes measurable dimensional drift. Industry documentation reports more than 20 hours of machining time per plate with 10 or more electrode changes -- each introducing potential alignment error and restart inconsistency. As tolerance specifications tighten, this progressive degradation directly threatens gas uniformity.

Heat-affected zone (HAZ): Surrounding each EDM hole is a zone where the bulk material's microstructure has been altered by thermal input. The HAZ exhibits changed grain structure, altered hardness, residual thermal stress, and modified corrosion resistance. For showerhead materials exposed to corrosive plasma chemistries, HAZ-induced property changes can accelerate degradation at hole boundaries.

Surface finish limitations: EDM as-machined surface roughness is typically Ra 0.2-6.0 um. Achieving finishes approaching 0.2 um Ra requires aggressive multi-pass strategies with decreasing discharge energy, adding substantial cycle time while still leaving recast residue.

Laser drilling uses focused light energy to ablate material. It can achieve small diameters (down to 0.025mm with specialized systems) and higher per-hole speed than EDM. However, laser-drilled holes exhibit taper from beam-focus geometry -- entrance diameter wider than exit -- which introduces flow non-uniformity. Research has documented that taper in drilled holes can cause significantly higher flow losses compared to ideal straight-walled geometry. Recast layers and heat-affected zones are present with nanosecond and microsecond pulse lasers. Ultrashort-pulse (femtosecond) lasers reduce thermal effects but at substantially lower throughput and higher equipment cost.

Mechanical drilling is constrained by tool wear (up to 5 um pore diameter deviation documented across production runs), burr formation at entry and exit, drill deflection at small diameters, and an inability to process hard alloys and ceramics. For microhole arrays at semiconductor-grade tolerances, mechanical drilling faces significant limitations for production micro-orifice arrays at advanced tolerances, though CNC methods serve some standard showerhead applications.

High-speed grinding serves a niche role for brittle materials such as silicon and silicon carbide showerheads, where the material's brittleness precludes conventional drilling.

5-axis CNC machining is used for manifold bodies, chamber components, and structural features, but faces the same tool wear and hard-material limitations as mechanical drilling for micro-orifice applications.

The cumulative impact of these limitations is not merely technical inconvenience -- it directly affects the semiconductor equipment manufacturer's competitive position. Within-wafer uniformity is the metric by which process tools are evaluated and qualified at customer fabs. Equipment manufacturers that win process-of-record (POR) status at leading-edge memory and logic fabs do so on the basis of uniformity specifications. If the showerhead manufacturing method introduces systematic non-uniformity through progressive tool wear, recast layer variability, or hole taper, that variability propagates through the gas distribution, into the plasma or deposition environment, and ultimately onto the wafer. At mature nodes, the process window was wide enough to absorb this manufacturing-induced variation. At sub-2nm GAA nodes and beyond, it is not. For equipment manufacturers competing on within-wafer uniformity specifications, manufacturing-induced yield variation in showerhead components directly impacts competitive position -- and this impact is felt at current production nodes, not only at future technology thresholds.

The industry's response to these limitations has been incremental: tighter electrode quality control, more frequent electrode changes, additional post-processing inspection steps, and increasingly aggressive acid washing protocols. Each of these measures adds cost and cycle time without addressing the fundamental mechanism. What the industry has not had is a manufacturing method that significantly reduces these limitations by operating on different physics entirely.

Where EDM Excels: EDM remains the established, proven method for showerhead manufacturing with decades of qualification data across the semiconductor equipment supply chain. For standard aluminum showerheads with moderate tolerance requirements and established designs, EDM's qualification infrastructure and broad supplier ecosystem represent significant value. When producing a small number of distinct hole geometries per plate, EDM per-hole throughput can be competitive with or exceed PECM. The installed base of EDM-qualified showerhead suppliers provides procurement flexibility that a newer technology cannot yet match.

Pictured: CMSX alloy superfinished via PECM

PECM Technology **Principles**

Pulsed Electrochemical Machining operates on a fundamentally different physics from all thermal and mechanical methods. Material is removed through controlled anodic dissolution -- an electrochemical process governed by Faraday's law of electrolysis.

The process sequence is as follows:

- A shaped cathode tool and the workpiece (anode) are positioned within a flowing electrolyte solution (water-based salt solution) with an inter-electrode gap maintained at tens of microns.
- Pulsed DC electrical current is applied. During each pulse-on phase, metal atoms at the workpiece surface dissolve into the electrolyte. The dissolution is highly localized to the areas closest to the cathode, providing geometric fidelity to the cathode tool shape.
- During each pulse-off phase, no current flows. Fresh electrolyte flushes the inter-electrode gap, removing dissolved metal ions and reaction byproducts, restoring uniform electrochemical conditions before the next pulse.
- The cathode tool is advanced toward the workpiece as material is removed, maintaining the precision gap.
- The cathode does not contact the workpiece at any point during the process.

The pulsed waveform is critical. Short pulse durations confine the active dissolution zone, achieving high geometric precision. The off-phase electrolyte flush eliminates the concentration gradients that limit conventional (continuous) ECM accuracy. This pulse-controlled approach is standard PECM technique, common across the industry. Voxel Innovations' proprietary implementation -- protected by international patents WO 2021/086455 A2 and WO 2021/242457 A2 -- incorporates a unique combination of cathode design, electrolyte flow management, and optimized machining parameters that enable the dimensional precision required for semiconductor-grade components.

The consequences of this mechanism are direct. The first four properties below are inherent to PECM process physics industry-wide; the performance specifications reflect Voxel Innovations' proprietary implementation:

Zero thermal input: No melting, no vaporization, no spark discharge. The process operates at room temperature.

Zero recast layer: Material is dissolved atom-by-atom. There is no re-solidification, no metallurgical alteration.

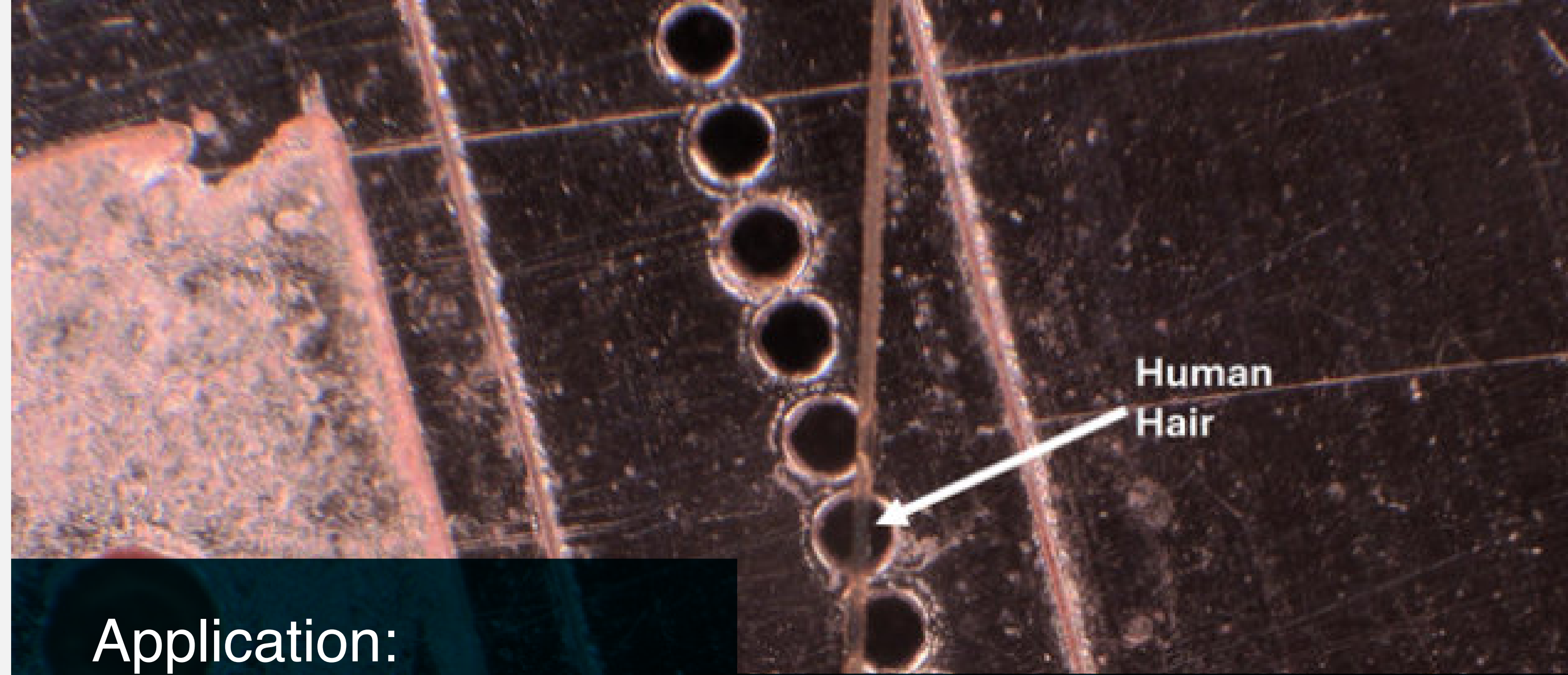
Zero heat-affected zone: No thermal energy enters the workpiece. Microstructure, grain structure, hardness, and corrosion resistance are preserved identically to the bulk material specification.

Substantially reduced tool wear: The cathode does not contact or erode against the workpiece. Cathode wear is significantly lower than EDM electrode wear. For large-feature applications, cathode life may span the full production volume. For small-feature applications, cathode wear becomes a factor requiring monitoring and periodic replacement. The key advantage is that wear is predictable and detectable, enabling correction before parts go out of specification.

Inherently burr-free: Electrochemical dissolution produces no mechanical shearing or material deformation. Edges are clean, and chamfers can be produced in the same operation.

Superior surface finish: The dissolution mechanism produces surface finishes below 0.4 um Ra, with results down to 0.1 um Ra achievable in a single operation -- verified in the Voxel Innovations process database and confirmed across 8+ published industry articles.

Material-hardness independence: Dissolution rate is governed by applied current and Faraday's law, not by material hardness. Inconel, Hastelloy, molybdenum, and aluminum are all machined with consistent geometric precision.



Application: **Semicon Showerheads**

PECM's process characteristics map directly to the requirements of semiconductor showerhead and gas distribution manufacturing across multiple component types and equipment divisions.

CVD & ALD **Showerhead Plates**

CVD showerheads represent the highest-volume, most precision-demanding gas distribution application. A typical CVD showerhead consists of a flat plate (approximately 12-14 inches in diameter for 300mm wafer tools) perforated with tens of thousands of micro-orifices in multi-zone concentric patterns. Hole diameters in the showerhead orifice context typically range from 0.254mm to 1.778mm (0.010" to 0.070") depending on zone and gas species, with aperture tolerances at current production specifications of approximately +/-10 um, with tightening expected at future nodes, and wall roughness specifications below 0.2 um Ra.

For new-generation CVD platforms with ultra-high vacuum architectures and zero-oxidation transport systems, the platform design philosophy explicitly demands contamination-free components. These platforms -- designed with wafer transport systems that eliminate atmospheric exposure between process steps -- invest significant engineering effort to prevent oxidation and contamination throughout the process sequence. A showerhead manufactured via EDM, carrying recast layers that require chemical stripping and subsequent re-contamination risk, introduces exactly the contamination source that the platform architecture was designed to eliminate. PECM's inherent contamination-free output aligns directly with this design philosophy by producing components that are specification-ready as-machined.

The economic argument reinforces the technical one. A single CVD showerhead plate can require more than 20 hours of EDM machining time, followed by acid washing, inspection, and potential rework. Multiple electrode changes during production introduce not only alignment risk but also idle time for setup. PECM's parallel cathode tooling approach -- where multi-featured cathodes address many orifices simultaneously -- offers a fundamentally different throughput model. While specific cycle time comparisons are geometry-dependent and validated during DFM engagement, the elimination of post-processing steps alone removes hours of non-value-added time from the manufacturing sequence.

Etch Gas **Distribution Plates** & **Electrode Support**

Plasma etch tools use gas distribution plates that may be separate from or integrated with the upper electrode assembly. In capacitively-coupled plasma (CCP) architectures, the upper electrode can serve dual duty as both RF electrode and gas distribution showerhead. The gas distribution plates themselves -- often constructed from aluminum, stainless steel, or nickel alloys -- face the same precision orifice requirements as CVD showerheads.

For etch applications where competitive market position depends on within-wafer etch uniformity, the consistency advantage of PECM's substantially reduced tool wear translates directly to process performance. When an equipment manufacturer's market share in demanding processes depends on uniformity specifications, the manufacturing method that produces highly consistent orifice geometry across the entire showerhead plate provides a measurable competitive advantage.

Showerhead Requirement	EDM Baseline	PECM Capability
Aperture tolerance (+/-10 μm current production)	Achievable but degrades with electrode wear over production run	High hole-to-hole consistency; <10 um repeatability published across multiple venues; reduced-wear mechanism prevents progressive drift
Wall roughness <0.2 μm Ra	0.2-6.0 um as-machined; requires multi-pass + acid wash to approach 0.2 μm	Below 0.4 um Ra, with results to 0.1 um Ra a achievable in single operation; exceeds typical showerhead specifications
Zero recast / zero HAZ	Recast always present; acid wash required	Inherent to process physics; no post-processing
Hole-to-hole consistency	Degrades across production run due to electrode wear	High consistency first to last; substantially reduced drift
Multi-zone patterns	Requires multiple electrode setups	Multi-featured cathode tooling addresses complex patterns
Burr-free orifice exits	Some burrs present; acid wash addresses	Inherently burr-free; chamfer-capable in single operation

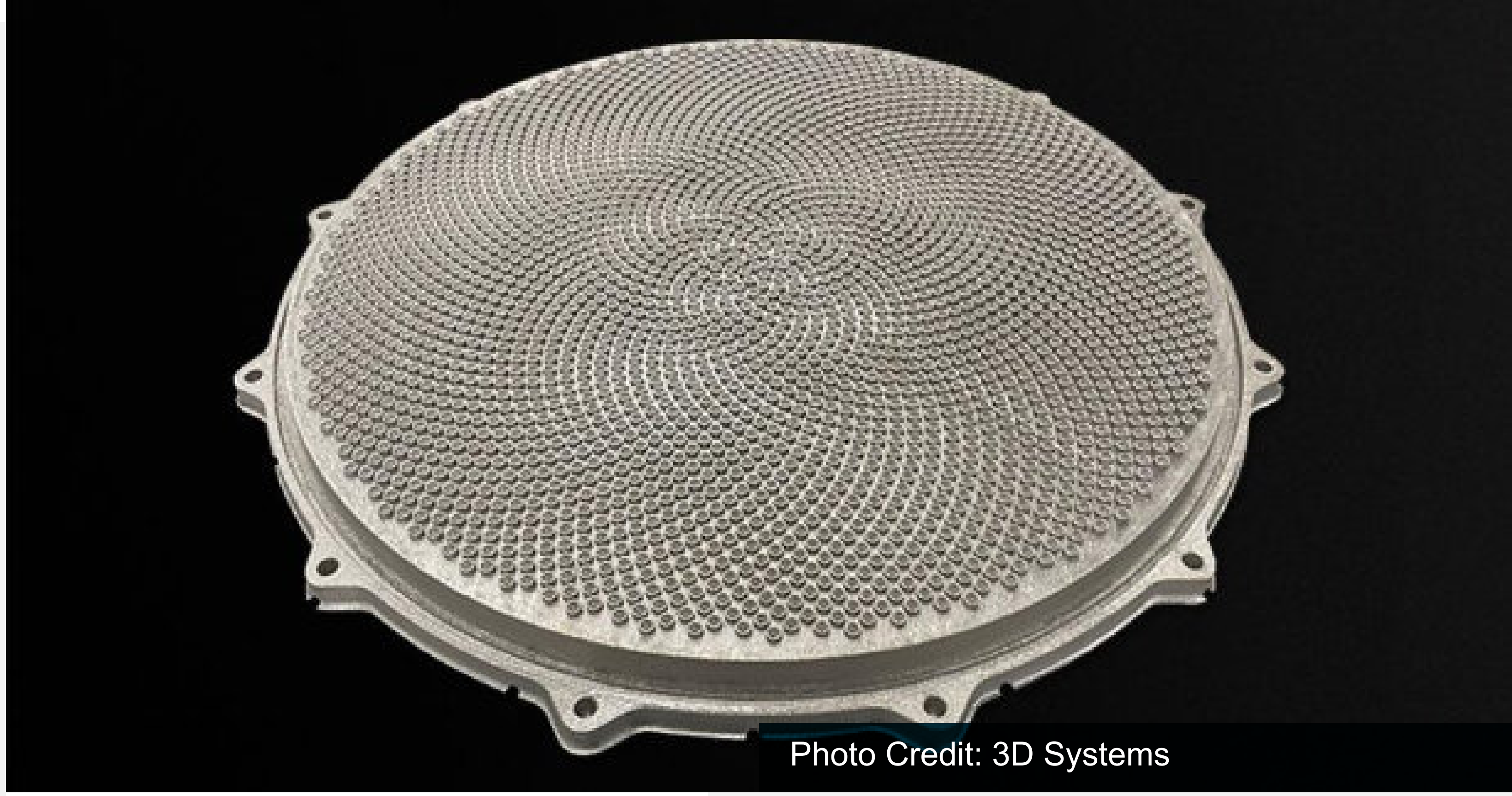


Photo Credit: 3D Systems

The etch application also highlights an important material consideration. Gas distribution plates in etch tools are often manufactured from nickel alloys (Inconel, Hastelloy) to withstand the corrosive fluorine and chlorine plasma chemistries used in etch processes. These work-hardening superalloys are among the most challenging materials for conventional machining methods -- EDM electrode wear accelerates significantly, mechanical drilling is effectively impractical, and tool costs escalate. PECM's material-hardness independence means that a nickel alloy gas plate is machined with the same geometric precision, at the same effective cost, as an aluminum plate. The hardness property that makes these materials desirable for corrosion resistance no longer constrains the manufacturing method selection.

Additionally, cryogenic etch environments operating at extreme low temperatures require precision cooling channels in chuck and chamber components that maintain dimensional stability across wide temperature ranges. PECM's room-temperature processing creates precision internal passages without any thermal distortion that would compromise dimensional stability under cryogenic operating conditions. The absence of residual thermal stress in PECM-manufactured components is particularly valuable for parts that will undergo repeated thermal cycling between room temperature and cryogenic extremes.

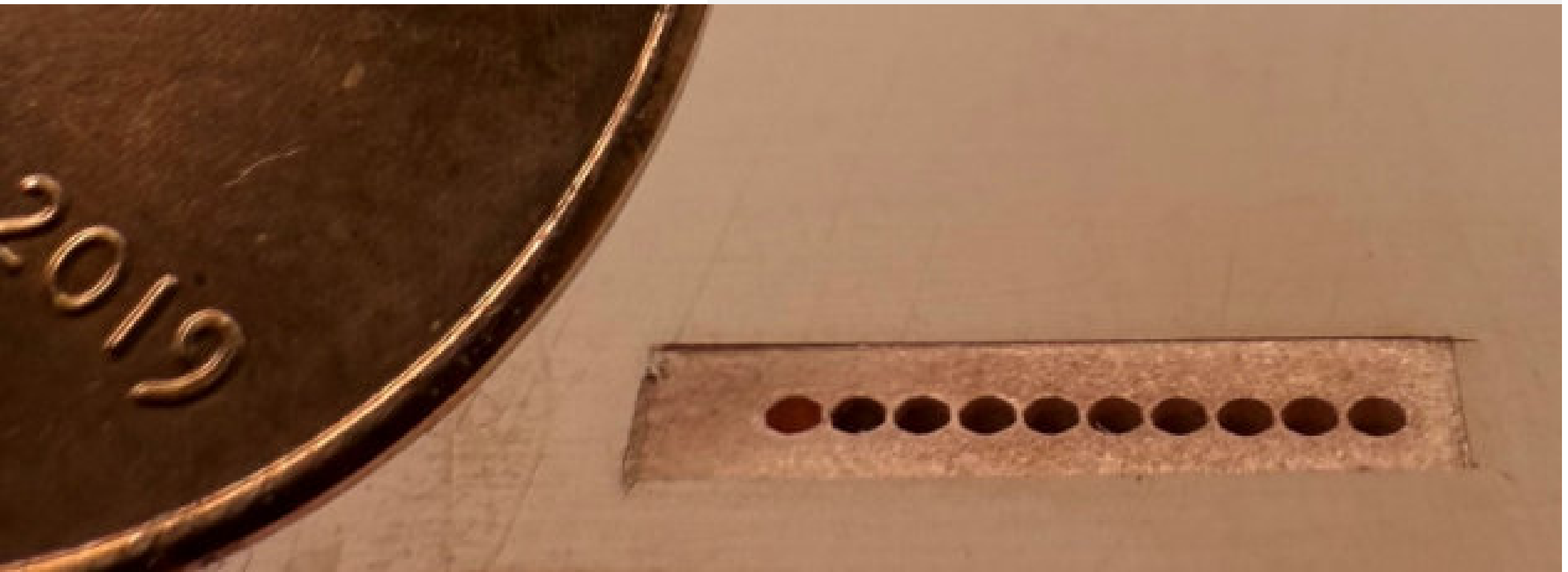
ALD **Gas Distribution Sections**

Spatial ALD architectures rotate wafers through distinct reaction zones, each requiring independent gas delivery with precise boundaries to prevent cross-contamination between precursor and reactant gases. The gas distribution components for each zone must maintain exact positional accuracy and orifice geometry to define sharp zone boundaries. Any blending of gas species between zones -- caused by inconsistent orifice geometry or flow non-uniformity -- degrades the self-limiting layer-by-layer deposition that is ALD's fundamental advantage over CVD for conformal coverage of high-aspect-ratio features.

Semi-batch ALD platforms that process multiple wafers simultaneously under continuous rotation amplify the precision demand. With up to six wafers per chamber rotating through gas zones at controlled speed, the gas distribution system must deliver identical process conditions to each wafer at each angular position. The orifice array for each zone must produce uniform flow that remains stable over thousands of rotation cycles per wafer lot. PECM's cathode-determined geometry and substantially reduced drift support the positional precision and long-term consistency these architectures demand.

Field Solutions **Replacement Components**

The semiconductor equipment industry's installed base of 96,000+ units generates substantial recurring demand for replacement showerheads, electrodes, and gas distribution plates. These replacement components have established specifications, reducing qualification risk. PECM's quality advantages -- no recast, burr-free, consistent dimensions -- directly support customer uptime service level agreements. Faster turnaround with higher quality positions PECM as a compelling supply path for the replacement parts market, which can represent multi-billion-dollar annual revenue streams for large equipment OEMs.



Implementation **Pathway**

Transitioning from EDM to PECM for showerhead manufacturing does not require wholesale replacement of existing production infrastructure. The recommended implementation approach follows a phased model.

Design for Manufacturability (DFM) Engagement: PECM introduces different design constraints than EDM. The cathode tool geometry defines the orifice array, and cathode design requires understanding of electrochemical dissolution characteristics for the specific workpiece material. Initial engagement includes DFM consultation to validate that existing showerhead designs are PECM-compatible or to identify design modifications that leverage PECM's unique capabilities (such as integral chamfers or complex orifice geometries that EDM cannot produce).

Prototype Evaluation: A representative showerhead section is manufactured via PECM and evaluated against the existing EDM baseline. Dimensional metrology, surface finish measurement, metallurgical cross-section analysis, and flow uniformity testing provide direct comparison data. Based on PECM performance in analogous precision applications, this evaluation is expected to demonstrate advantages in surface quality, consistency, and contamination-free surfaces, while identifying any geometry-specific process optimization needed.

Quality Validation: Standard supplier qualification protocols apply. PECM-manufactured components are tested against the same specifications as EDM components. Process capability data (Cpk), dimensional repeatability across production runs, and material characterization documentation support the qualification pathway. Voxel Innovations maintains AS9100D and ISO 9001:2015 certifications.

Production Ramp: Following qualification, production scales through the cathode tooling model. The primary non-recurring engineering (NRE) investment is cathode tool development. Once qualified, the cathode is reusable across substantial production volumes with significantly reduced degradation compared to EDM electrodes -- unlike EDM electrodes that are consumed during production. Per-part variable costs are dominated by electricity and electrolyte, both commodity inputs.

Qualification Timeline: Semiconductor equipment component qualification typically requires 9-18 months of validation. This timeline is driven by the OEM's internal quality gates, not by PECM process maturity. Early engagement during new platform development cycles -- when component specifications are being defined and supplier qualification is underway -- provides the most efficient path to production qualification.

Total Cost of Ownership Considerations: Direct per-hole cost comparison between PECM and EDM is geometry-dependent and evaluated on specific showerhead designs during DFM engagement. However, the TCO framework extends well beyond per-hole machining cost. PECM significantly reduces or eliminates several cost centers that are built into the EDM production model:

Cost Element	EDM (Current)	PECM
Machining cost per plate	Baseline (established)	**Geometry-dependent**; parallel processing offers throughput pathway
Electrode/tooling replacement	Ongoing; 10+ per plate at significant per-electrode cost	**One-time NRE**; substantially reduced ongoing degradation
Acid wash post-processing	Required for every plate (chemical cost + time + + disposal)	**Eliminated**
Deburring	Required	**Eliminated**
Secondary finishing	Often required to meet surface spec	**Eliminated** (*specification met as-machined*)
Inspection burden	*Intensive (compensating for wear-induced variation)*	*Cathode-specific quality protocols required; reduced progressive drift simplifies dimensional monitoring but does not eliminate inspection requirements*
Scrap from recast-related defects	Present	**Eliminated**
Chemical waste disposal	Acid wash and dielectric fluid	**Water-based electrolyte** (low environmental impact)

PECM: **Design Considerations/Limitations**

No manufacturing process is universally optimal. PECM's electrochemical mechanism introduces its own set of design considerations that must be evaluated for each application.

Corner Geometry: PECM dissolution tends to round sharp internal corners due to current density distribution in the inter-electrode gap. Designs requiring sharp internal radii may need geometry modification or secondary processing. This is a known characteristic of electrochemical material removal.

Cathode NRE Investment: Each unique orifice pattern or feature geometry requires dedicated cathode tooling. Cathode design is an iterative engineering process requiring specialized expertise, with development timelines of weeks to months and NRE investment typically starting at $50,000 or more. This investment is justified for production volumes but makes PECM unsuitable for rapid prototyping or one-off components.

Cathode Wear Considerations: While cathode wear is substantially lower than EDM electrode wear, it is not zero -- particularly for small-feature applications where current density is concentrated. Cathode monitoring protocols and periodic replacement are part of the production process. The advantage is that wear is predictable and detectable, enabling correction before parts go out of specification.

Material Constraints: PECM requires electrical conductivity in the workpiece. Non-conductive materials (ceramics, polymers, non-doped silicon) cannot be processed. Some refractory metals with stable oxide layers present additional challenges, though recent advances are expanding the processable material range. Workpiece bulk electrical resistivity must be below approximately 0.01 ohm-cm.

Electrolyte Management: The electrochemical process generates dissolved metal ions and reaction byproducts in the electrolyte. Electrolyte composition, temperature, and flow rate must be actively managed for consistent results. Waste electrolyte requires proper handling and disposal, though the environmental impact is generally lower than EDM dielectric fluid disposal or acid washing chemicals.

Not Suited for Simple Geometries: For applications involving simple holes, flat surfaces, or basic geometric features where conventional CNC machining is effective, PECM's tooling investment is not justified. PECM's value emerges when conventional methods face limitations -- hard materials, micro-features, complex 3D geometries, high-volume repeatability requirements, or contamination-free surfaces.

Volume Threshold: The NRE investment in cathode tooling means PECM becomes cost-effective at production volumes. For very low quantities (prototyping, fewer than several hundred parts), conventional methods are typically more economical. The break-even point is application-dependent and evaluated during DFM engagement.

Multi-Division **Opportunity**

Semiconductor OEMs with multiple product divisions create multiple application vectors for PECM:

Deposition Division: CVD showerhead plates (aluminum, nickel alloys), ALD gas distribution sections, multi-zone gas manifolds, PVD chamber gas delivery components. Highest showerhead density per tool; active platform transitions create procurement windows.

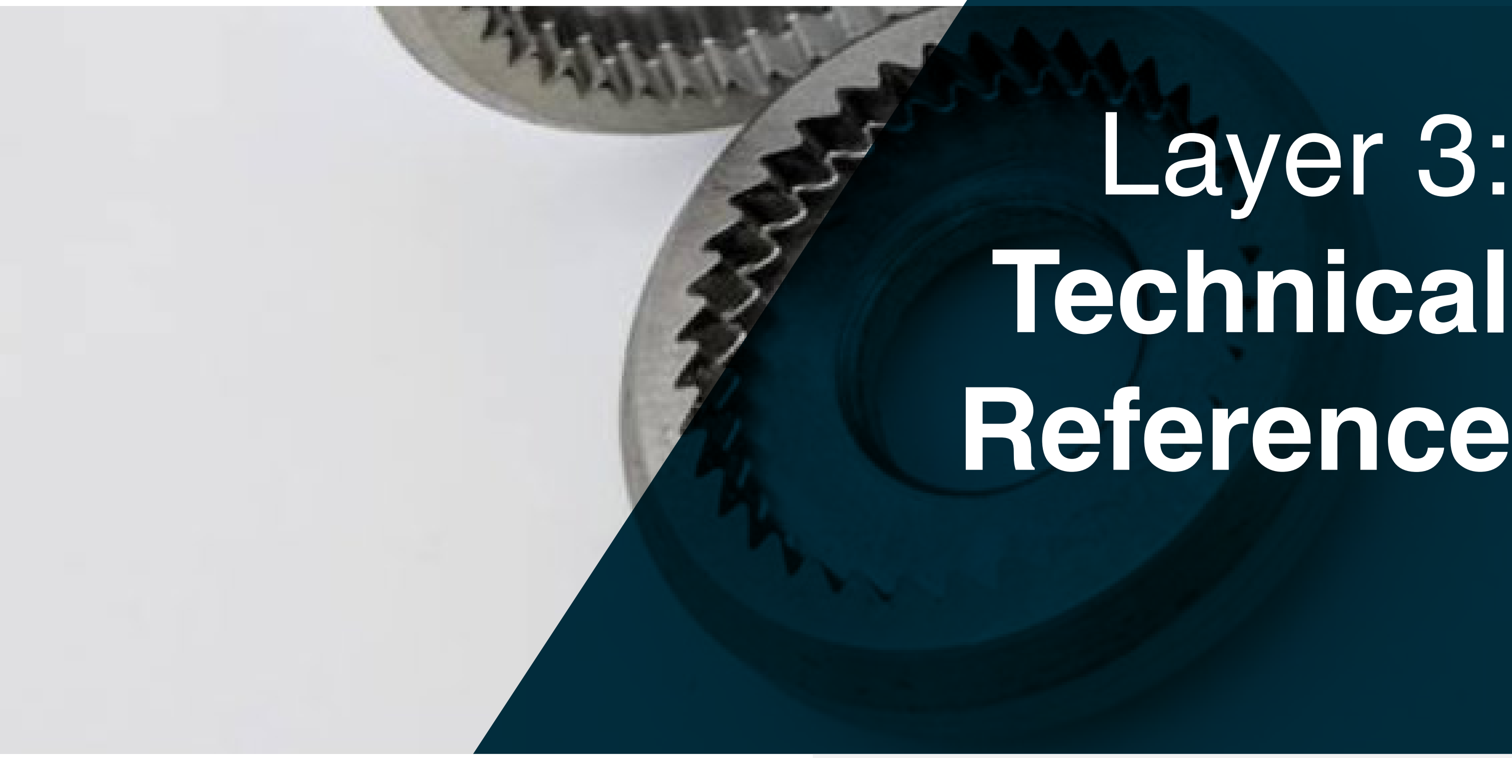
Etch Division: Gas distribution plates (aluminum, stainless steel, nickel alloys), electrode support gas delivery components, cryogenic etch cooling channels. Largest revenue division; competitive market position depends directly on component quality.

Field Solutions: Replacement showerheads and gas distribution plates across all tool types in the installed base. Lower qualification barrier because specifications are established. Recurring demand independent of new tool shipments.

Clean/Surface Preparation Division: Cryogenic aerosol nozzle arrays, chemical delivery manifolds, gas cluster ion beam components. Moderate PECM relevance; internal channel quality and nozzle precision are applicable.

A successful demonstration in one division provides a proof point that can be referenced when engaging adjacent divisions, but each requires its own qualification process. This independence also means that qualification in one division does not depend on adoption in another.

A single manufacturing technology can generate multiple engagement pathways within one OEM. The gas distribution challenges across divisions share enough technical commonality that PECM process knowledge transfers efficiently, while component-specific requirements (materials, orifice geometries, operating environments) ensure that each division's application is distinct, offering yjr opportunity to build a broad, resilient relationship anchored in demonstrated capability rather than dependence on any single product line.



Layer 3: **Technical Reference**

PECM Process **Fundamentals**

PECM is a subtractive manufacturing process based on the principle of anodic dissolution. The workpiece (anode) and a shaped cathode tool are immersed in a flowing electrolyte solution. When pulsed DC current is applied, metal atoms at the workpiece surface oxidize and dissolve into the electrolyte according to Faraday's law:

$$m = (M\,I\,t) / (n * F)$$

Where m is mass removed, M is molar mass of the workpiece metal, I is current, t is time, n is the valence of the dissolving metal ion, and F is Faraday's constant (96,485 C/mol).

The process operates at room temperature. No phase change (melting or vaporization) occurs in the workpiece material. Material removal is atom-by-atom through electrochemical oxidation, not through thermal energy input.

Inter-electrode gap: Maintained at tens of microns between cathode and workpiece. This narrow gap is critical for geometric precision -- the closer the cathode, the higher the current density and dissolution rate, providing shape fidelity.

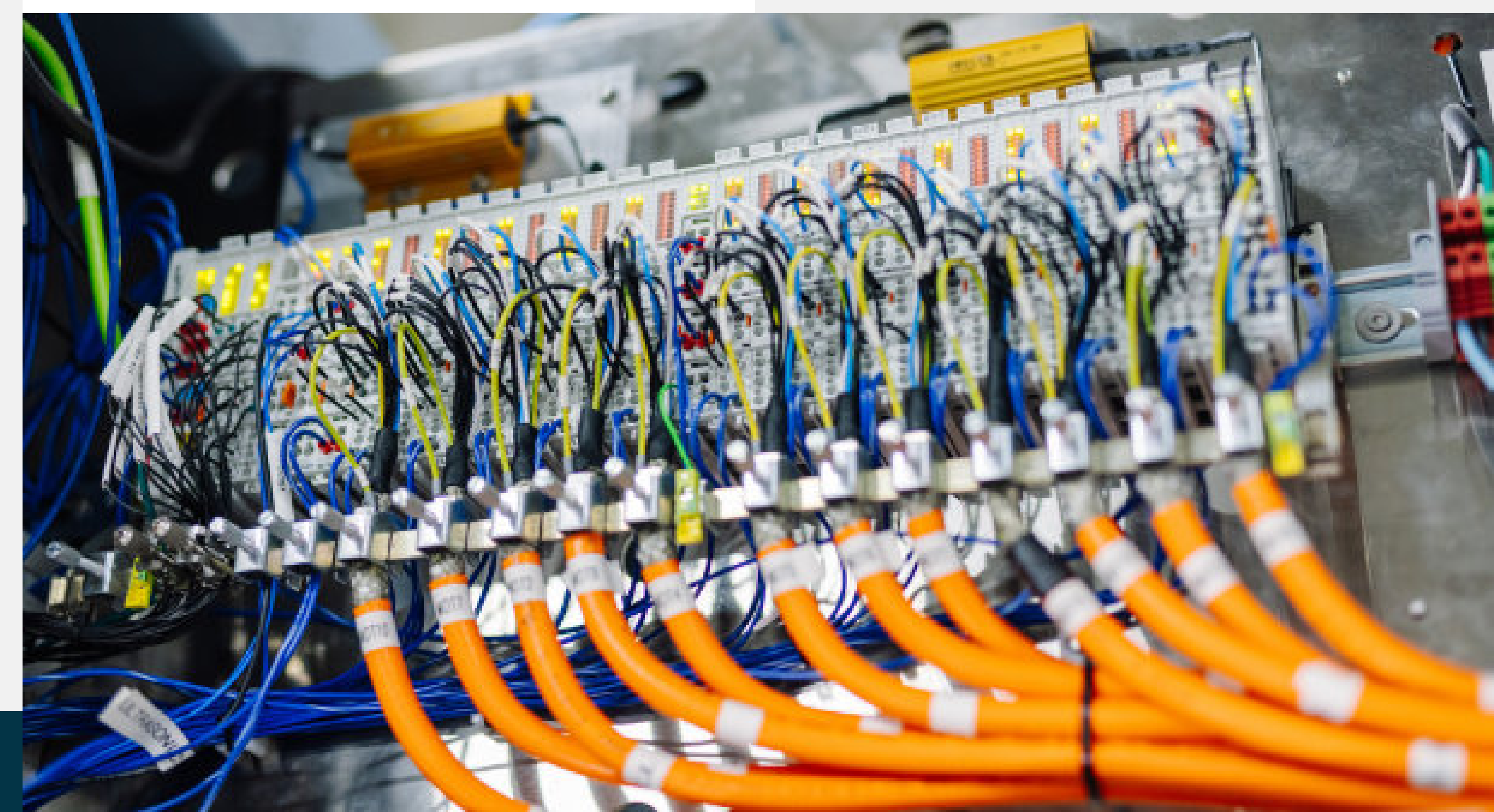
Pulsed waveform: Short current pulses (microsecond to millisecond duration) confine the dissolution zone. Between pulses, fresh electrolyte flushes the gap, removing dissolved ions and restoring uniform conditions. This pulse-flush cycle is the mechanism that enables PECM to exceed the precision of conventional continuous-current ECM.

Cathode tool: A shaped electrode (typically copper, stainless steel, or specialized alloy) whose geometry defines the inverse of the desired feature geometry on the workpiece. The cathode does not participate in the electrochemical reaction -- it serves only as the current-carrying counter-electrode. Cathode wear is substantially lower than in contact-based processes. No cathode material is transferred to the workpiece.

Electrolyte: Water-based salt solutions (typically sodium chloride or sodium nitrate, depending on workpiece material). The electrolyte serves three functions: (1) carries current between cathode and anode, (2) transports dissolved metal ions away from the dissolution zone, and (3) maintains thermal equilibrium in the inter-electrode gap.

Voxel Innovations' Proprietary PECM Process: A proprietary implementation incorporating a unique combination of cathode design, material selection, and current density optimization, alongside patented electrolyte flow management systems (WO 2021/086455 A2) and optimized machining methods (WO 2021/242457 A2). This combination enables precision and repeatability beyond standard PECM capabilities.

Note: PECM as an industry-standard process is offered by multiple vendors worldwide. The specifications and performance data in this document reflect Voxel Innovations' specific implementation, which is optimized for the precision microhole and surface finishing applications relevant to semiconductor gas distribution.



Material **Compatibility Matrix**

Material	PECM Suitability	Semicon Application	Process Notes
Aluminum alloys (6061-T6, cast Al)	Excellent	Standard CVD showerheads; most common showerhead material by volume	Dissolves cleanly in appropriate electrolytes; good thermal conductivity; commonly anodized post-machining for corrosion protection
316L Stainless Steel	Excellent	Gas delivery manifolds, chamber components, internal plumbing	Extensive PECM demonstration history; proven in UHP component manufacturing
Inconel 625/718	Excellent	High-temperature showerheads and gas plates for corrosive plasma environments	PECM significantly reduces the severe tool wear and work-hardening challenges that make Inconel difficult for conventional machining; consistent precision as soft metals
Hastelloy C-22/C-276	Excellent	showerheads in fluorine and chlorine chemistry environments	Dissolves uniformly regardless of work-hardened state; no reduced feed rates or accelerated tooling costs
Pure Nickel (Ni 200/201)	Excellent	-electroless Ni plating substrates	Predictable dissolution; consistent results
Molybdenum-based alloys	Excellent	High-temperature CVD environments exceeding aluminum thermal limits	Conductive refractory metal; PECM-compatible. Electrolyte optimization is application-specific
Copper (OFHC, C101)	Excellent	Thermal management components, heat spreaders	Eliminates burring problems endemic to mechanical machining of soft copper
High-purity silicon (doped)	Unknown	Upper electrode/ showerhead assemblies for CCP etch (consumable)	Silicon is a semiconductor; PECM requires electrical conductivity. Heavily doped silicon (0.005-0.02 ohm-cm resistivity) may be processable but has not been validated.
CVD Silicon Carbide	Unknown	Ultra-pure showerheads for demanding process environments	Conductivity depends on doping and crystal structure; CVD-SiC for semiconductor applications may be semi-insulating.
Aluminum Nitride (AlN)	Not compatible	Thermal management + gas distribution combination components	AlN is an electrical insulator; PECM cannot process non-conductive materials
Ceramics (Al2O3, Y2O3)	Not compatible	Chamber liners, plasma-facing surfaces	Insulating materials are outside PECM's addressable scope

Process **Parameter Ranges**

Parameter	Value	Verification Source
Surface finish (Ra)	Below 0.4 um Ra; results to 0.1 um Ra achievable	Published in 8+ industry articles; CEO-calibrated: '0.1 um Ra plenty good for this application'
Tool/cathode wear	Substantially reduced; cathode life geometry-dependent. Large features: cathode may span full production volume. Small features: periodic monitoring and replacement required.	CEO-corrected language; process physics (non-contact cathode); published in 8+ industry articles
Thermal damage	None (room-temperature process)	Fundamental to process physics (electrochemical dissolution); confirmed in all published PECM literature
Burr condition	Inherently burr-free	Fundamental to process physics (no mechanical shearing)
Recast layer	None	Fundamental to process physics (no melting/re-solidification)
Residual stress	None (stress-free)	No mechanical or thermal forces on workpiece
Aspect ratio -- deep features	Up to 300:1 (Extreme High Aspect Ratio)	PECM process documentation; STEM drilling capability
Aspect ratio -- thin walls	20:1 achieved in thin-wall channel features (0.075mm ribs in stainless steel); semiconductor orifice aspect ratios require geometry-specific validation	Voxel PECM capability; thin-wall context -- not semiconductor orifice drilling
Thin wall minimum	0.050mm (50 um)	CEO-confirmed PECM capability (A6); 0.075mm demonstrated in thin-wall channel features
Hole consistency	High consistency across arrays; <10 um repeatability published in multiple venues. Specific tolerances are geometry-dependent.	Published whitepapers and industry articles; reduced-wear cathode mechanism
Parallel machining	Hundreds to thousands of features simultaneously	Multi-featured cathode tooling
Electrolyte	Water-based salt solutions	Standard PECM process chemistry
Inter-electrode gap	Tens of microns	Process parameter documentation
Certifications	AS9100D, ISO 9001:2015	Voxel Innovations quality system
Patents	WO 2021/086455 A2, WO 2021/242457 A2	International PECM process patents
Production proof point	130,000 parts/week across all production verticals, 24/7 operations, 3 production lines	Validated production capacity (not semiconductor-specific volume)

Comparative **Performance Data**

Parameter	PECM	EDM	Laser Drilling	Mechanical Drilling
Surface finish (Ra)	Below 0.4 um Ra, with results to 0.1 um Ra achievable	0.2-6.0 um (0.1-0.4 um best case with multi-pass)	1-10 um (recast present)	0.4-3.2 um
Recast layer	None	Always present (5-30 um thick)	Present (nanosecond/ microsecond lasers)	None
Heat-affected zone	None	Present (altered microstructure)	Present (grain growth, phase changes)	Minimal (friction heat only)
Tool/electrode wear	Substantially reduced; predictable and detectable	Progressive; 10+ electrode changes per 12-inch plate	Minimal (optics degradation over time)	Significant; up to 5 um diameter drift
Burr formation	None (inherently burr-free)	Some; requires acid wash	Spatter/dross at edges	Significant entry/exit burrs
Hole wall parallelism	Parallel (cathode-determined)	Generally parallel with some taper	Tapered (Gaussian beam geometry)	Generally parallel but wear-dependent
Hole-to-hole consistency	High consistency across array (substantially reduced drift mechanism)	Degrades across production run	Variable (taper, recast variability)	Degrades with tool wear
Aspect ratio capability	Voxel PECM: 20:1 achieved in thin-wall channel features; STEM drilling: up to 300:1	Up to ~20:1	Up to ~10:1 (taper trade-off)	Up to ~5:1 (microholes)
Residual Stress	None	Thermal Stress	Thermal stress	Mechanical stress
Micro Alteration	None	Yes (recast + HAZ)	Yes (HAZ)	Minimal

voxel

www.voxelinnovations.com

Contact our Team

WHY VOXEL?

Voxel integrates our **PECM technology** with **unique process expertise** to enable **repeatable**, production-rate manufacturing of complex metal parts for critical industries with key credentials:

- **Proprietary PECM process (patented)**
- **WO 2021/086455 A2, WO 2021/242457 A2**
- **AS9100D, ISO 9001:2015**
- **130K units/week across 24/7 production lines**
- **US-based manufacturing (NC)**
- **Active development programs in semicon**

GET IN TOUCH WITH OUR ENGINEERS:

520 Hinton Pond Road STE 128
Knightdale, NC 27545

984-464-0701

info@voxelinnovations.com

www.voxelinnovations.com

Partnership **Roadmap**

1 Engagement

Start a conversation about your goals and challenges; share relevant examples.

2 Discovery & Qualification

Assess project fit by reviewing geometry, materials, and production targets.

3 Solution Shaping

Define a clear manufacturing path via transparent discussion of requirements and risk.

4 Proposal & Negotiation

Review detailed scope, pricing, and assumptions; refine terms for alignment.

5 Commitment

Formalize partnership, assign resources, and establish communication channels.

6 Feasibility

Validate manufacturability via PECM trials, inspection, and parameter tuning.

7 Repeatability

Demonstrate consistent part quality across multi-part runs with documented controls.

8 Scalability

Prepare tooling, capacity and throughput for cost-effective, high-volume production.

9 Ramp-Up

Launch initial production runs: optimizing for speed, quality and delivery assurance.

10 Full Production

Deliver reliable, efficient supply while supporting long-term improvement & growth.