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WHITE PAPER

ADVANCED THIN FILM DEPOSITION WITH THE EVAP-4 MINI E-BEAM EVAPORATOR

A Comprehensive Technical Analysis

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White Paper Author: Dr. Joyce Joseph
Based on experimental research and technical analysis by:
Dr. Vicky Broadley Dr. Srinivasa Rao Saranu, Mark Vaughan and the Nikalyte Engineering Team
Nikalyte Ltd, United Kingdom

Executive Summary

The EVAP-4 series mini electron beam evaporators represent a paradigm shift in thin film deposition technology, offering researchers and manufacturers an economical, compact alternative to traditional large-scale electron beam hearths. This white paper presents a comprehensive analysis of the EVAP-4 system's capabilities, drawing upon extensive experimental data for materials ranging from noble metals to refractory compounds. Our findings demonstrate exceptional versatility across diverse material systems, with particular emphasis on process optimisation, geometric considerations, and practical implementation strategies for both the High Capacity Four Pocket (EVAP-4) and Compact Four Pocket (EVAP-4C) configurations.

1. Introduction

1.1 Background

Electron beam evaporation has long been the preferred method for depositing high-purity thin films in applications ranging from semiconductor fabrication to optical coatings. Traditional e-beam systems, whilst highly capable, present significant barriers to entry: substantial capital investment, considerable footprint requirements, and complex operational protocols. The EVAP-4 series addresses these challenges whilst maintaining the precision and material versatility demanded by modern research and production environments.

Figure 1: Evap-4 mounted inside the PVD chamber with pocket 3 powered up.

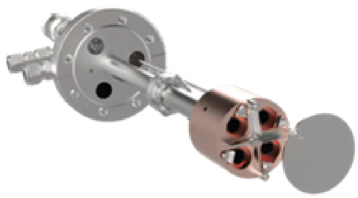
1.2 System Architecture

The EVAP-4 platform comprises two distinct configurations:

High Capacity Four Pocket Mini E-Beam (EVAP-4):

Optimised for larger substrate applications, this configuration features extended pocket geometry (in vacuum diameter: 57 mm) offering improved co-evaporation capability at moderate working distances. The system accommodates both 2 mm and 4 mm diameter rods, as well as 1000 mm³ crucibles for lower melting point materials.

HIGH CAPACITY 4 POCKET EVAP-4



Compact Four Pocket Mini E-Beam (EVAP-4C):

Designed for space-constrained installations, this variant maintains four-pocket functionality within a reduced envelope (in vacuum diameter 34mm). The compact geometry necessitates longer working distances for equivalent substrate coverage but offers enhanced portability and integration flexibility.

COMPACT 4 POCKET EVAP-4C

Both systems employ independent flux monitoring plates positioned above each pocket, enabling real-time deposition rate measurement and closed-loop process control a critical capability for multi-material co-evaporation applications.

2. Noble and Common Metal Deposition

The EVAP-4 platform demonstrates exceptional versatility across diverse material systems, from noble metals with moderate melting points to challenging refractory compounds. Figure 2 presents a comprehensive overview of achieved deposition rates, illustrating the three-order-of-magnitude performance range

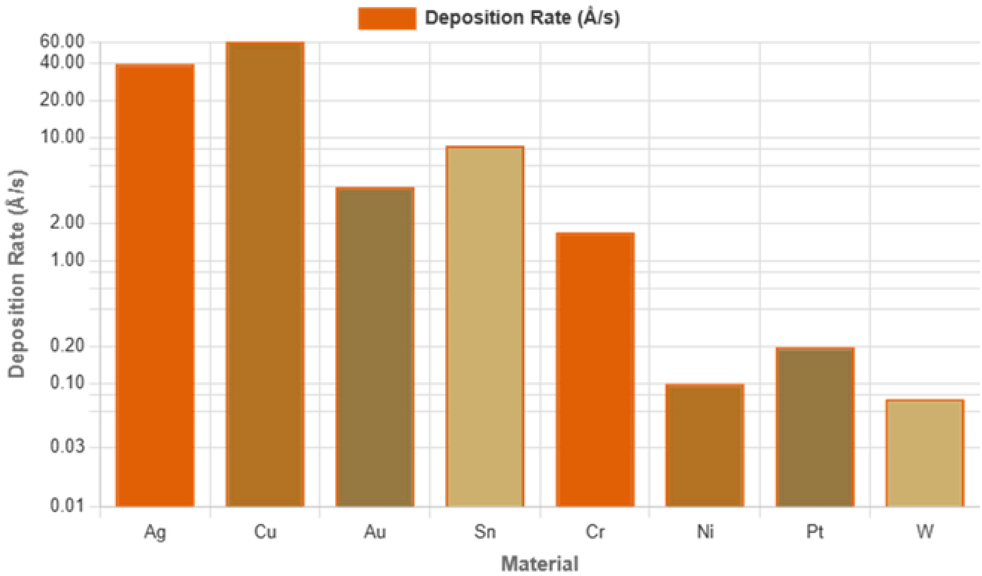


Figure 2: Comparative deposition rates across material portfolio demonstrating exceptional versatility from noble metals (Ag, Au, Cu) to refractory compounds (Pt, W). Note logarithmic scale accommodating three orders of magnitude range. [1], [5], [6], [7]

2.1 Silver (Ag)

Silver deposition trials revealed exceptional deposition rates, achieving 40 Å/s at 70 W power with a 200 mm working distance. The material exhibited excellent containment within molybdenum crucibles, with no observable creep beyond the crucible boundary. The deposition process itself remained highly stable throughout extended 1.5-hour runs, demonstrating the system's robustness for production applications.

2.2 Gold (Au)

Gold demonstrated outstanding performance characteristics, with stable deposition rates up to 4 Å/s at 150 W. The material exhibited excellent wetting behaviour within tungsten crucibles, facilitating efficient heat transfer and uniform evaporation. Ion flux measurements proved exceptionally stable above 65 W, achieving 550 nA at maximum power, sufficiently high to enable flux-based process to control independent of QCM feedback. The strong linear correlation between flux current and deposition rate positions gold as an ideal candidate for multi-pocket co-evaporation applications where independent rate control is paramount.

2.3 Copper (Cu)

Copper evaporation trials demonstrated the system's capability for high-throughput processes, achieving deposition rates of 60 Å/s at 146 W. The material exhibited strong linear correlation between flux and deposition rate up to 15 Å/s, enabling precise process control within this regime. Tantalum crucibles proved suitable for containment, though material buildup was observed at higher deposition rates.

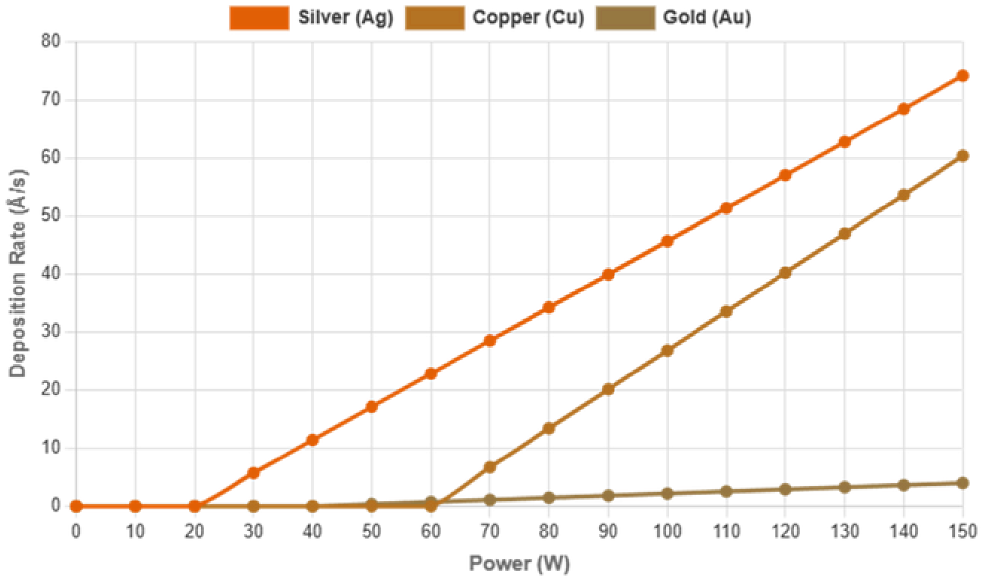


Figure 3: Power-dependent deposition characteristics for silver, gold, and copper. Linear relationships enable predictable process scaling and straightforward power optimisation for target rates.[7]

2.4 Nickel (Ni):

Characterised by its high melting point (1455°C), nickel required careful thermal management. Deposition rates of 0.1 Å/s were achieved at 125 W, with stable flux currents throughout. However, thermal expansion mismatch between tungsten crucibles and PbN liners necessitates careful power ramping protocols. Rod-based evaporation with extended filaments offers a promising alternative for applications requiring thin nickel films (5-10 nm).

2.5 Tin (Sn):

Despite its low melting point (232°C), tin's poor vapour pressure requires temperatures approaching 1000°C for practical deposition rates. The material achieved 8.6 Å/s at 150 W with 100 mm working distance, demonstrating expected $1/r^2$ scaling. Crucible liner implementation is recommended to prevent flux plate shorting due to material creep.

2.6 Chromium (Cr):

Chromium's propensity to sublime below its melting point (1907°C) facilitates efficient evaporation. Moderate deposition rates of 1.7 Å/s were recorded at 150 W, with excellent flux stability (33 nA) maintained throughout extended runs. The material demonstrated consistent performance across varying working distances, validating the flux monitoring system's independence from geometric factors.

2.7 Titanium (Ti):

Titanium presented challenges when evaporated from crucibles, achieving only 0.05 Å/s at 160 W. Post-deposition inspection revealed localised melting at the crucible-slug interface, indicating insufficient thermal coupling. Rod-based evaporation is strongly recommended for titanium applications requiring practical deposition rates.

3. Refractory Materials: Platinum and Tungsten

3.1 Platinum (Pt) with Carbon Support Sleeves

Platinum's combination of high melting point (1768°C) and low vapour pressure presents substantial challenges for conventional evaporation methods. Initial trials using rod-based and crucible-based approaches proved unsuccessful: rod evaporation resulted in bulk melting rather than localised tip heating, whilst crucible methods suffered from alloying with containment materials.

The breakthrough came through implementation of carbon support sleeves, hollow carbon rods surrounding the platinum feedstock. This configuration maintains the molten platinum tip in proximity to the filament whilst preserving electrical bias capability. The carbon material proved non-reactive with platinum, contrasting sharply with molybdenum support attempts that resulted in detrimental alloying.

Optimised Configuration:

- Carbon sleeve: 16.5 mm length, 5.5 mm diameter
- Platinum rod: 29 mm length, 2 mm diameter
- 3 mm diameter reservoir machined in sleeve top
- QCM working distance: 120 mm

Stable deposition rates of 0.2 Å/s were achieved, with flux remaining consistent throughout the evaporation process. The system successfully transitioned to higher deposition rates with gradual power increases, though rates exceeding 0.7 Å/s proved impractical due to carbon sleeve degradation at elevated power levels.

Key findings:

- Carbon support sleeves enable reliable Pt evaporation
- Stable operation at 0.2 Å/s demonstrated
- Process window limited by carbon sleeve evaporation above 0.7 Å/s
- Method suitable for precision platinum thin film applications

3.2 Tungsten (W) with Shaped Rod Design

Tungsten represents perhaps the most challenging material for thermal evaporation, combining an exceptionally high melting point (3410°C) with poor vapour pressure. Successful tungsten evaporation demands innovative approaches to power density management.

The solution employed a dual-strategy approach: geometric optimisation of the tungsten feedstock combined with enhanced electron emission geometry. The standard 4 mm × 28 mm tungsten rod was machined to create a tapered profile, progressively narrowing from 4 mm at the base to 1.4 mm in the middle section, terminating in a 1.9 mm diameter tip. This geometry concentrates thermal energy at the evaporation point whilst maintaining mechanical stability and ease of mounting.

Complementing this geometric optimisation, a circular filament design was implemented, surrounding the rod to maximise electron current delivery. This configuration enabled stable tungsten evaporation at powers up to 160 W the system's filament current limit, achieving deposition rates of 0.075 Å/s at 70 mm working distance.

Rod Geometry Specifications:

- Top section: 1.9 mm diameter, 10 mm length
- Middle section: 1.4 mm diameter, 6 mm length
- Bottom section: 4.0 mm diameter (standard), 12 mm length

Both power control and ion flux control modes demonstrated stable operation above 140 W, with good agreement between control methodologies. However, discrepancies emerged at lower powers (<140 W), recommending flux control implementation only for powers exceeding this threshold.

Key findings:

- Shaped rod design with circular filament enables W evaporation
- Maximum deposition rate of 0.075 Å/s at 160 W, 70 mm working distance
- Flux control suitable for process powers >140 W
- Demonstrates mini evaporator capability for extreme melting point materials

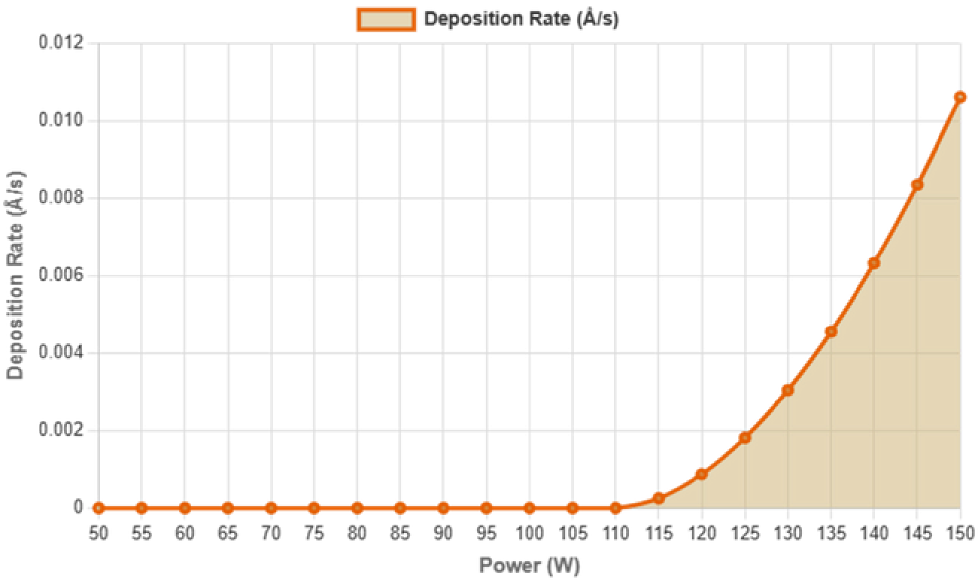


Figure 4: Tungsten deposition rate versus applied power using optimised shaped rod geometry and circular filament configuration. The steep increase above 140 W validates the enhanced thermal management approach, achieving 0.075 Å/s at 160 W, a breakthrough for mini e-beam platforms. [1]

4. Working Distance Optimisation and Geometric Considerations

4.1 Overlap Distance Fundamentals

Uniform thin film deposition across extended substrate areas whether for co-evaporation or sequential multi-layer processing, demands precise understanding of the geometric relationship between source configuration and deposition uniformity. The overlap distance (d) represents the diameter of the region where emission cones from adjacent pockets intersect at a given working height (h).

The evaporation cone geometry is governed by several critical parameters:

- Rod diameter (r)
- Rod-to-top-plate distance (x)
- Top plate thickness (t)
- Top plate opening (L)
- Inter-pocket spacing (z)

4.2 System Comparison: EVAP-4 vs EVAP-4C

Comparative analysis reveals substantial differences in overlap characteristics between the two system configurations.

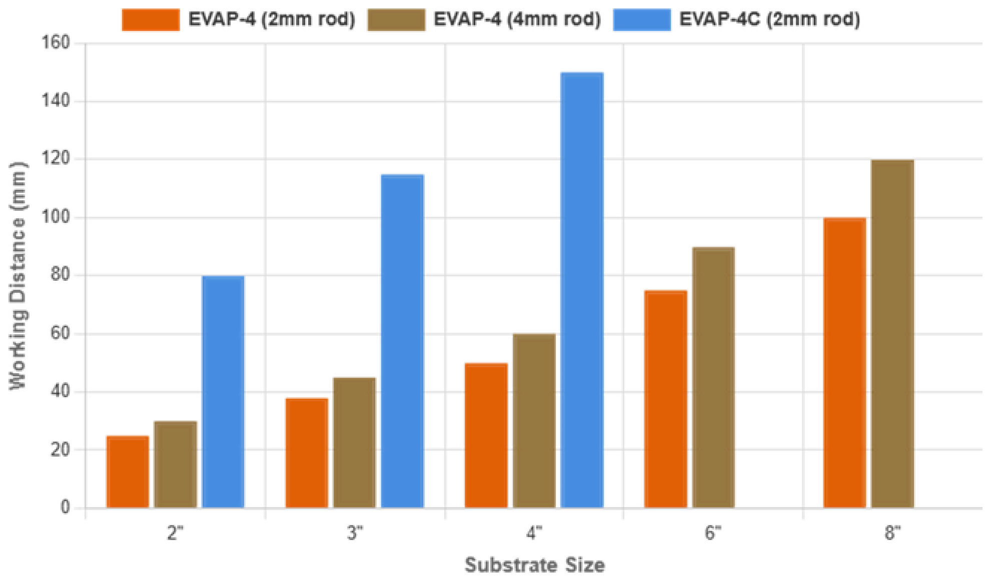


Figure 5: Minimum working distance requirements for uniform deposition across substrate sizes. EVAP-4 accommodates full 8" wafers at 100 mm whilst EVAP-4C optimises for 2-3" applications, illustrating the geometric trade-offs between the two configurations. [3][4]

EVAP-4 Performance:

At 200 mm working distance with a new 27 mm rod, the EVAP-4 achieves a maximum overlap diameter of 451 mm sufficient for uniform deposition across full 8" wafers (203.2 mm) at 100 mm working distance. This generous overlap provides significant process latitude but introduces heightened sensitivity to rod consumption.

EVAP-4C Performance:

The compact configuration yields a maximum overlap diameter of 141 mm at 200 mm working distance. Whilst more modest, this proves adequate for 2" wafer (50.8 mm) processing at 80 mm working distance. The reduced overlap translates to diminished sensitivity to geometric variations a beneficial characteristic for extended production runs.

5. Process Control Strategies

5.1 Flux-Based Control Architecture

The EVAP-4 series' integrated flux monitoring system represents a important feature in mini ebeam process control. Independent flux plates positioned above each pocket measure the ion current generated during material vaporisation typically several nanoamperes to hundreds of nanoamperes depending on material and power level.

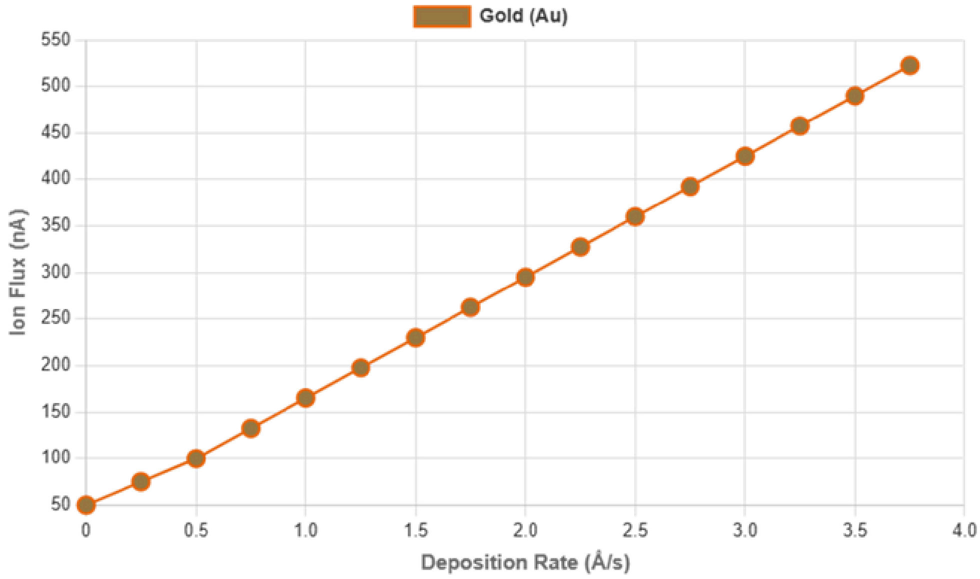


Figure 6: Ion flux versus deposition rate for gold, demonstrating exceptional linearity ($R^2 > 0.98$) above 65 W. This stable correlation enables QCM-independent process control particularly valuable for co-evaporation applications where individual pocket monitoring is essential. [7]

The ion flux exhibits direct proportionality to deposition rate, providing an alternative measurement methodology independent of QCM limitations. This capability proves particularly valuable for:

- Multi-pocket co-evaporation requiring independent rate control
- Extended depositions where QCM crystals approach frequency limits
- Materials producing QCM interference or unreliable readings

5.2 Control Mode Selection

Power Control Mode:

Maintains constant electrical power delivery to the pocket, suitable for materials exhibiting stable evaporation characteristics and minimal geometric evolution during processing. This mode simplifies setup for single-material depositions and shorter runs.

Flux Control Mode:

Actively adjusts power to maintain target ion flux, compensating for geometric changes, material depletion, and thermal variations. Particularly recommended for:

- Tungsten evaporation (>140 W)
- Extended high-rate depositions
- Multi-hour production runs
- Materials sensitive to rod consumption effects

5.3 Practical Recommendations

Pre-Deposition Planning:

- Calculate expected overlap diameter for sample size and initial rod length
- Estimate rod consumption rate based on target thickness and deposition rate
- Set working distance accounting for minimum rod length during run
- Verify flux-rate correlation for new materials or rod geometries

Process Monitoring:

- Record rod length at installation
- Monitor both QCM thickness and flux throughout deposition
- Document any flux instabilities or QCM anomalies
- Inspect flux plates and pockets post-run for coating or shorting

Optimisation Strategies:

- Implement power ramping protocols (particularly for materials in PbN liners)
- Use crucible liners to minimise material creep for low-melting-point metals
- Ensure flux plate ceramics shielding is used to prevent coating -induced shorting
- Consider rod-based evaporation for materials showing poor crucible performance.

6. Material Selection Guidelines

6.1 Crucible-Based Evaporation

Recommended for materials with melting points <2000°C:

Material	Crucible	Liner	Max Power	Rate (Å/s)	Notes
Silver	Mo	Optional (Alumina)	70 W	40	High rate, excellent containment
Gold	Mo, W	No	150 W	4	Stable flux, ideal for co-evap
Copper	Mo, Ta	Recommended (Alumina)	160 W	60	Very high-rate capability
Tin	Ta	Yes (Alumina)	150 W	8.6	Requires liner for creep control
Chromium	W	No	150 W	1.7	Excellent stability
Nickel	W	PbN	125 W	0.1	Ramp up power slowly to equalize thermal expansion.
Titanium	W	No	160 W	0.05	Rod evaporation preferred

6.2 Rod-Based Evaporation

Recommended for materials with melting points >2500°C or poor crucible compatibility:

Material	Rod Diameter	Special Requirements	Max Rate	Notes
Tungsten	4 mm (shaped)	Circular filament, tapered tip	0.075 Å/s	Extreme melting point
Platinum	2 mm	Carbon support sleeve	0.2 Å/s	Prevents bulk melting
Titanium	2-4 mm	Standard filament	TBD	Superior to crucible
Nickel	2-4 mm	Extended filament	TBD	Alternative to crucible
Molybdenum	2-4 mm	Circular filament	TBD	High melting point
Niobium	2-4 mm	Circular filament	TBD	High melting point

7. Maintenance and Longevity Considerations

7.1 Filament Life and Replacement

Filament longevity depends strongly on operating power and duty cycle. The 1.3 A current limit implemented as a hard limit in the power supply protects filaments from catastrophic burnout, but sustained high-power operation (particularly for refractory materials) necessitates periodic inspection and replacement.

Recommended practices:

- Inspect filaments visually before each extended run
- Replace filaments showing signs of embrittlement or discolouration
- For circular filaments, verify concentricity with rod tip
- Maintain inventory of standard and circular filament configurations
- Operation of mini evaporator at pressure < 1x10-5mbar

7.2 Crucible and Pocket Inspection

Regular inspection of crucibles and pocket assemblies prevents process failures and extends component life:

Crucibles:

- Check for cracks or deformation after high-temperature runs
- Monitor material creep patterns and use crucible liners where recommended
- Verify PbN liner fit and condition for thermally mismatched materials
- Clean or replace crucibles showing signs of alloying or contamination

Pockets:

- Inspect for material buildup on pocket walls and remove flakes that could cause a short
- Verify flux plate cleanliness and freedom from shorts
- Check grub screw condition and tightness
- Monitor for signs of coating on pocket insulators

7.3 Flux Plate Management

Flux plate maintenance proves critical for reliable process control:

- Visual Inspection: Check for material coating after each deposition, particularly for high-rate materials (Ag, Cu, Sn)
- Electrical Testing: Verify flux plate isolation resistance periodically
- Cleaning Protocol: Remove coating buildup before insulation resistance degrades

8. System Integration and Installation

8.1 Chamber Configuration

The EVAP-4 series' compact form factor enables installation on a variety of port configurations:

- Upward-facing ports: Optimal for crucible-based evaporation, gravity assists material containment. Standard 2¾" conflat flange compatibility ensures broad chamber compatibility.
- Angled ports (30°): Acceptable for most applications but introduces asymmetric melt distribution in crucibles. Requires consideration during working distance calculations.
- Horizontal ports: Suitable only for rod-based evaporation; crucible applications impractical due to material distribution challenges.

8.2 Working Distance Accommodation

Chamber geometry must accommodate target working distances plus rod length evolution:

Minimum chamber depth calculation:

Required depth = Working distance + Rod length + EVAP-4 height + Safety margin

For example, 200 mm working distance applications with 27 mm rods require chamber depths exceeding 260 mm, accounting for the EVAP-4 body and flange dimensions.

8.3 QCM Positioning

Optimal QCM placement balances several factors:

- **Co-evaporation applications**: Position QCM within overlap region to measure composite deposition rate. Verify position remains within overlap area accounting for rod consumption.
- **Sequential deposition:** QCM positioning less critical but should maintain consistent working distance to all active pockets for accurate tooling factor application.
- **Extended depositions**: Consider multiple QCM positions or indexing mechanisms to prevent single-crystal frequency limit issues.

8.4 Vacuum Requirements

Base pressure requirements vary by material but generally:

- Noble metals (Ag, Au, Cu): $<5\times10^{-7}$ mbar adequate
- Reactive metals (Ti, Cr): $<2\times10^{-7}$ mbar preferred
- Refractory materials (W, Pt): $<1\times10^{-7}$ mbar recommended

Ensure chamber pumping capacity maintains pressure during deposition; high-rate evaporation (e.g., Ag at 40 Å/s) can produce measurable pressure increases.

9. Conclusion

The EVAP-4 series mini electron beam evaporators successfully challenge the conventional wisdom that high-performance thin film deposition demands large, expensive infrastructure. Through innovative source design, intelligent process control, and careful geometric optimisation, these compact systems deliver capabilities previously reserved for traditional e-beam hearths.

10. Key achievements demonstrated

- **Material Versatility:** Successful evaporation across extraordinary material diversity from silver's 961°C melting point to tungsten's 3410°C validates the platform's adaptability. Innovative approaches such as shaped rod designs for tungsten and carbon support sleeves for platinum extend the accessible material palette into traditionally challenging regimes.
- **Process Control:** Integrated flux monitoring provides robust, QCM-independent deposition rate measurement and control. The demonstrated stability of flux-based control for materials ranging from gold to chromium enables sophisticated multi-material processes with independent rate management.
- **Geometric Understanding:** Comprehensive characterisation of overlap distance and area evolution with rod consumption empowers users to optimise working distances for their specific applications. The quantified sensitivity to rod diameter, length, and positioning enables predictive process planning rather than empirical trial-and-error.

- **Practical Implementation:** Extensive deposition data across eight materials provides concrete starting points for process development. The documented relationships between power, flux, and deposition rate accelerate new material integration whilst highlighting material-specific considerations (crucible selection, liner requirements, flux stability).
- **Economic Accessibility:** Perhaps most significantly, the EVAP-4 series demonstrates that research-grade thin film deposition need not demand six-figure capital investment or dedicated facility infrastructure. The compact form factor and straightforward integration democratise access to e-beam evaporation for resource-constrained laboratories.

These mini e-beam evaporators deliver research-grade performance in a compact, affordable package across academic research, and prototyping.

References

[1] Nikalyte, "Evaporating Tungsten in the Evap-4 Mini E-beam Evaporator", Technical Note 14. [Online]

[2] Nikalyte, "Impact of Rod Lifetime on Working Distance in the Mini E-Beam Evaporator", Technical Note 13. [Online]

[3] Nikalyte, "Evaluating Working Distance Parameters for the High Capacity Four Pocket Mini E-Beam EVAP-4", Technical Note 12. [Online]

[4] Nikalyte, "Evaluating Working Distance Parameters for the Compact Four Pocket Mini E-beam Evaporator EVAP-4C", Technical Note 11. [Online]

[5] Nikalyte, "Efficient Platinum Evaporation with the Compact Four Pocket Mini E-beam Evaporator EVAP-4C", Technical Note 10. [Online]

[6] Nikalyte, " Deposition Rates and Flux Currents for Nickel, Tin, Chromium, and Titanium Using Mini E-beam Evaporator Evap-4", Technical Note 6. [Online]

[7] Nikalyte, "Deposition Rates and Flux Currents for Silver, Gold, Copper and Aluminum Using Mini E-beam Evaporator Evap-4," Technical Note T05. [Online]

Appendix A: Quick Reference Tables

A.1 Material Compatibility Matrix

Material	Melting Point	Crucible Type	Liner Required	Rod Compatible	Max Rate	Relative Difficulty
Ag	961°C	Mo	Optional, Alumina	Yes	40 Å/s	Easy
Au	1064°C	Mo, W	No	Yes	4 Å/s	Easy
Cu	1085°C	Mo, Ta	Recommended Alumina	Yes	60 Å/s	Easy
Sn	232°C	Ta	Yes, Alumina	No	8.6 Å/s	Moderate
Cr	1907°C	W	No	Yes	1.7 Å/s	Moderate
Ni	1455°C	W	PbN	Yes	0.1 Å/s	Moderate
Ti	1668°C	W	No	Yes (preferred)	0.05 Å/s (crucible)	Challenging
Pt	1768°C	Not suitable	N/A	Yes (C-sleeve)	0.2 Å/s	Challenging
W	3410°C	Not suitable	N/A	Yes (shaped)	0.075 Å/s	Very Challenging

A.2 Working Distance Guidelines (EVAP-4)

Substrate Size	Minimum Working Distance (2mm rod)	Minimum Working Distance (4mm rod)
2" (50.8 mm)	25 mm	30 mm
3" (76 mm)	38 mm	45 mm
4" (101.6 mm)	50 mm	60 mm
6" (152.4 mm)	75 mm	90 mm
8" (203.2 mm)	100 mm	120 mm

Note: Add 15-20% safety margin to account for rod consumption during extended runs

A.3 Working Distance Guidelines (EVAP-4C)

Substrate Size	Minimum Working Distance (2mm rod, new)
2" (50.8 mm)	80 mm
3" (76 mm)	115 mm
4" (101.6 mm)	150 mm

Appendix B: Troubleshooting Guide for EVAP-4 Operation

Symptom	Possible Causes	Solutions
Flux instability	Coating on flux plate ceramics	Inspect and clean flux plates; implement shielding
Low deposition rate	Excessive working distance	Reduce working distance; increase power
	Rod consumed significantly	Replace rod; recalculate overlap distance
	Insufficient power	Verify power supply output; check filament condition
Material creep	High vapour pressure material	Implement crucible liner (PbN or Ta)
	Excessive temperature	Reduce power; verify working distance
Flux plate shorting	Material buildup bridging insulators	Clean flux plates; implement regular inspection schedule
	High-rate deposition coating components	Use PbN liner to reduce creep; reduce deposition rate
Asymmetric melt	Angled port installation	Account for asymmetry in crucible loading; consider upward port
	Uneven heating	Verify filament position and condition
PbN liner displacement	Thermal expansion mismatch	Slow power ramp rates; verify crucible/liner tolerances
	Excessive power	Reduce maximum power; monitor during ramp
Poor rod evaporation	Insufficient electron current	Verify filament-to-rod alignment; check bias voltage
	Rod too large diameter	Use shaped rod design; reduce tip diameter
QCM reading unstable	Multiple material deposition	Use flux control for individual pocket monitoring
	Crystal approaching frequency limit	Replace QCM crystal; use flux as backup measurement
Alloying with crucible	Incompatible crucible material	Refer to compatibility matrix; try alternative crucible
	Temperature too high	Reduce power; verify material melting point requirements

Appendix C: Geometric Calculations

C.1 Overlap Distance Formula

For two diagonal pockets separated by distance z, with top plate opening L, thickness t, rod diameter r, and rod-to-top-plate distance x, the overlap diameter d at working height h is given by:

$$d = 2h \times \tan(\theta) - z$$

where $\theta = \arctan[(L/2 - r/2)/(x + t)]$

C.2 Deposition Rate Scaling

The deposition rate R at working distance h follows inverse-square law:

$$R(h_2) = R(h_1) \times (h_1/h_2)^2$$

For example, a material depositing at 4 Å/s at 100 mm will deposit at 1 Å/s at 200 mm.

C.3 Rod Consumption Estimation

For a cylindrical rod of diameter d and initial length L_0, the rod length L after depositing thickness t over area A is approximately:

$$L = L_0 - (4 \times A \times t)/(\pi \times d^2 \times \rho)$$

where ρ is the material density. This assumes uniform material density and neglects evaporation losses.

Appendix D: Material Properties Reference

Material	Melting Point	Boiling Point	Density	Vapour Pressure at MP	Key Characteristics
Silver (Ag)	961°C	2162°C	10.49 g/cm³	Low	High conductivity, excellent corrosion resistance
Gold (Au)	1064°C	2856°C	19.32 g/cm³	Very low	Oxidation resistant, stable, noble metal
Copper (Cu)	1085°C	2562°C	8.96 g/cm³	Low	High thermal/electrical conductivity
Tin (Sn)	232°C	2602°C	7.31 g/cm³	Very low	Low melting point but high evaporation temperature
Chromium (Cr)	1907°C	2671°C	7.19 g/cm³	Moderate	Sublimes readily below melting point
Nickel (Ni)	1455°C	2913°C	8.91 g/cm³	Very low	Strong atomic bonds, magnetic
Titanium (Ti)	1668°C	3287°C	4.51 g/cm³	Low	Reactive, strong, lightweight
Platinum (Pt)	1768°C	3825°C	21.45 g/cm³	Very low	Extremely stable, catalytic properties
Tungsten (W)	3410°C	5555°C	19.25 g/cm³	Extremely low	Highest melting point of all metals

Contact Information

Nikalyte Ltd , 77 Heyford Park,
Heyford Park Innovation Centre,
Upper Heyford, Bicester
OX25 5HD, United Kingdom
For technical enquiries, application support, or system specifications:
Visit www.nikalyte.com or write to us at sales@nikalyte.com
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- Mark Vaughan for extensive noble metal characterisation, flux-rate correlation studies, and platinum carbon sleeve methodology development
- The Nikalyte engineering team for meticulous experimental execution, data collection, and systematic validation across eight material systems
- All technical insights, experimental protocols, performance data, and process recommendations originate from their research efforts.
- Special recognition to early adopters of the EVAP-4 mini ebeam evaporator who provided invaluable feedback contributing to continuous refinement of both hardware and operational protocols.

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Version	Date	Changes	Author
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