TITLE OF THE INVENTION

Adaptive Point-of-Use Chemical-Dosing Cartridge with Integrated Multi-Parameter Inline Sensing for Semiconductor Wet-Processing

FIELD OF THE INVENTION

The present disclosure relates to semiconductor manufacturing equipment and, more particularly, to point-of-use (POU) systems that meter ultra-high-purity chemical concentrates into a continuously flowing base liquid used during wafer-level wet processes such as photo-resist development, edge-bead removal, single-wafer cleaning and immersion-lithography water conditioning. The disclosure addresses real-time, closed-loop control of chemistry concentration, ionic contamination and nano-particle content at the sub-second time scale required for sub-10 nm device fabrication.

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BACKGROUND

1. Conventional chemical-delivery architecture

In most 200 mm and early 300 mm fabs, high-volume chemicals (developers, HF dilutions, RCA solutions, surfactants) are prepared in **bulk day-tanks or chemical-distribution units (CDUs)** located in the sub-fab. A CDU typically:

- receives 200 L drums of concentrate,
- blends or dilutes to a set concentration using flow-meters or gravimetric pumps,
- filters and degasses the mixture, and
- pressurises a PFA header that feeds one or more tools.

The blended bath volume is usually **1–20 L** at each point-of-use (POU) tank inside the coater/developer track or wet bench.

2. Limitations of the bulk-batch / open-loop model

Limitation	Impact on advanced nodes
Long residence time (minutes–hours). Conductivity or pH is checked off-line every 30-60 min, so operators overdose concentrate by 20–30 % to avoid falling under the lower spec limit.	Elevated chemical cost; concentration drift causes critical-dimension (CD) and defect excursions.
Sampling latency. Nano-particles or trace metal spikes propagate through several wafers before SPC or lab titration reports the outlier.	Yield loss, especially for immersion EUV where one particle > 25 nm can print a repeating watermark defect.
Tank-change downtime. Swapping a 200 L drum requires nitrogen purge and line qualification, stopping the track for 30–90 min.	Lost scanner/track availability valued at €100 k–200 k h^{-1} at current wafer ASPs.
Inadequate real-time metallurgy. Legacy blenders measure only flow or refractive index; they cannot detect < 10 ppt metal	Sub-ppb ionic spikes corrode lines, introduce stochastic defects and degrade overlay.

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ions or < 30 nm particles demanded by sub-7 nm nodes (SEMI F57/F104).

3. Partial solutions and their shortcomings

- **On-demand blenders** (e.g., DFS "Fusion™", US 9 591 596 B2) meter concentrate and DI water only when the tool requests a batch. Although they reduce bath volume, they remain *open-loop* during the dispense and usually sense only conductivity or density.
- **Track-integrated canisters** (TEL ACT series, FSI dispense mod-cans) supply pre-diluted developer but lack inline ppb-level ionic monitoring or sub-second feedback.
- **External filtration (Entegris, MKS), degassing, or UV-TOC** equipment cleans the chemistry but does not actively correct excursions once the fluid leaves the CDU.
- **SEMI E87/E90 host logs** capture flow-meter data after the fact; they cannot prevent real-time defects.

Consequently, present approaches fail to guarantee ±0.5 % concentration and sub-ppt purity **in the milliseconds immediately before the liquid reaches the wafer**, creating an unsolved problem for EUV, high-NA immersion and future gate-all-around nodes.

4. Industry need

Advanced lithography cells now require:

- **Millilitre-scale "micro-batches"** generated for every wafer instead of litre-scale baths,
- **Multi-parameter sensing—ionic ppb, 5 nm particles, pH, conductivity, temperature—sampled ≥ 5 Hz**,
- **Closed-loop actuation** that injects or withholds concentrate within ≤ 0.6 s of detecting an excursion, and
- **Automated SEMI-compliant genealogy** that records each pulse for regulatory and yield-debug audits.

No commercial CDU, on-demand blender or track canister presently satisfies these simultaneous requirements. The adaptive cartridge system disclosed herein is designed to fill this technological gap while fitting inside the existing chemical-bay footprint of coater/developer tracks and immersion-water loops.

The invention is industrially applicable to fabrication of integrated-circuit wafers, compound-semiconductor devices and flat-panel displays.

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DESCRIPTION

Smart-Cartridge™ Adaptive Point-of-Use Micro-Blender

Technical Specification & Preferred Embodiment

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1 | System purpose & scope

Smart-Cartridge™ replaces legacy "dumb" chemistry canisters in a lithography coater/developer (track) or immersion-water loop.

It delivers **closed-loop, sub-second dosing** of a single, high-purity concentrate into a continuous base stream (DI water or rinse solvent), holding wafer-side concentration ±0.5 % while cutting chemical use 30–40 %.

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2 | Functional requirements

#	Requirement	Target / tolerance
F-1	Maintain developer molarity, HF-dilute ratio, or surfactant ppm to **±0.5 % of set-point**wafer-by-wafer	≤0.6 s sensor-to-correction latency
F-2	Detect ionic contamination spikes ≥ 5 ppt and particle bursts ≥ 25 cnt mL^{-1} (>25 nm)	Trigger adaptive flush in ≤ 0.4 s
F-3	Log **SEMI E143 XML** record per dispense (time stamp, sensor vector, valve strokes, cartridge ID)	≥99.9 % record integrity

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F-4	Quick-swap liner change-over **< 5 min** without line purge	Operator wears standard track PPE
F-5	Meet SEMI F57 / F104, S2 / S8, E84 / GEM300 safety & comm. standards	Third-party report on file

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3 | Embodiment overview

PTFE/PFA Smart-Head (re-usable, 3-5 yr life)

└── 20 L PFA liner bottle (disposable)

├─ Key-coded QCII / SLQC connector (≤10 µL dead leg)

├─ Integrated sensor manifold

│ • Conductivity 0.01–20 µS cm^{-1} (±0.5 %)

│ • pH 1–14 (±0.01)

│ • Ionic cell <0.01–50 ppt (±0.005 ppt)

│ • Particle counter 5 nm–50 µm (±0.1 cnt mL^{-1})

│ • Temperature –10 °C–100 °C (±0.2 °C)

├─ Piezo isolation valve (Cv 0.2, 25 ms open)

└─ RFID/NFC tag (chem ID, batch, expiry)

STM32H7 MCU board (400 MHz, 2 MB flash)

└── Adaptive control FW

• PID @ 1 kHz

• Hierarchy tiers (QC-1, QC-2, PM-1, ES-1)

• MQTT + SECS-II/GEM, OPC-UA

» 24 Vdc / 48 Vdc power from track service bay

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4 | Mechanical specifications

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Parameter	Value	Note
Smart-Head envelope	300 mm H × 180 mm W × 120 mm D	Slides into TEL/SCREEN track chem bay
Liner capacity	5 L, 10 L, 20 L (field-selectable)	One-piece stretch-blow PFA
Wetted materials	PFA 450HP, PTFE, PEEK, Kalrez 7075 seals	All < 10 ppt metal extractables
Valve duty	5 Hz max, 25 ms min pulse	Delivers 1–100 mL per pulse
Static mixer	50 mL Kenics micro-helix (PFA)	Residence < 0.05 s @ 6 mL s^{-1}

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5 | Electrical & software

5.1 Electronics

- STM32H7 @ 400 MHz, FPU; 2 MB flash, 1 MB RAM
- Dual 16-bit SAR ADCs sampling sensors at 10 kS s^{-1} (averaged to 10 Hz)
- RS-485 / Ethernet (SECS-II GEM, OPC-UA), CAN-FD for multi-head daisy chain
- 24 Vdc logic, 48 Vdc 2 A valve driver (MOSFET H-bridge)
- OLED 0.96″ status screen + tricolour LED

5.2 Firmware

- Scheduler: pre-emptive RTOS (FreeRTOS)
- Control library: PID + Smith predictor (dead-time 0.25 s)
- Hierarchy ISR priorities: QC-1 & ES-1 > QC-2 > PM-1
- Embedded TLS 1.3 encryption for log upload
- Fail-safe: power-loss closes valve (NC)

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6 | Process-control performance

Chemistry	Base flow	Pulse size	±Spec achieved	Typical chem cut
Developer 2.38 % TMAH	300 mL wafer^{-1}	40 mL concentrate	±0.4 %	35 %
EBR solvent	15 mL wafer^{-1}	10 mL	≤ 5 ppt metals	30 %
Surfactant rinse	1 L wafer^{-1}	2 mL	±0.5 ppm	30 %
Immersion DI surfactant	20 L min^{-1} loop	0.1 mL	±0.5 ppm; <15 cnt mL^{-1} (>25 nm)	40 %
UPW ionic trim	50 L min^{-1} plant	0.1 mL	<3 ppt total ions	—

Latency (sensor → wafer): ≤ **0.6 s** worst-case all chemistries.

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7 | Safety & compliance

- **SEMI S2 / S8** full report (TÜV)
- **CE & UL 61010-2-040** electrical safety
- **ATEX Zone 2** optional for solvent cartridges (n-BA, PGME)
- **IP 65** Smart-Head enclosure; liner passivation 200 °C DI rinse
- Leak detection port; dual PTFE rupture discs @ 3 bar

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8 | Operation & maintenance

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Task	Interval	Time	Tool downtime
Liner swap	per interval table (7–42 d)	< 5 min	None (swap bay)
Sensor auto-cal (cond./pH)	90 d	10 min	None
Valve stroke count rebuild	1 M pulses (~2 yr)	15 min	None
Full Smart-Head overhaul	3–5 yr	1 h (swap spare)	None

Predictive-maintenance module flags sensor drift (>3 σ baseline) and valve torque rise (+15 %) 3–4 weeks before failure.

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9 | Interfacing & data

- **GEM300**: E30, E37, E40, E87, E90, E94, E116, E172 (E143 batch records)
- **OPC-UA** real-time tag set (sensor vector, valve state, liner ID)
- **MQTT** optional push to factory FDC; 256-bit AES end-to-end
- Log buffer: 90 days @ 1 k records s^{-1} (32 GB eMMC)

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10 | Embodiment variants

Variant ID	Chemistry compatibility	Valve Cv	Sensors omitted / added
SC-TMAH-20	TMAH, KOH, TMAH-developer	0.2	full 5-in-1 stack
SC-SOLV-10	PGME, n-BA, acetone	0.15	ionic + particle - pH

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SC-HF-Trim	49 % HF dilute (100:1, 300:1)	0.1	cond + temp + ORP
SC-DI-Surf	Surfactant stock (2 %)	0.05	cond + particle
SC-UPW-Chel	Chelator trim (sub-ppt)	0.02	ionic + resistivity

Each variant shares the same Smart-Head electronics; only liner, wetted seals and sensor calibration EEPROM differ.

Best-Mode Contemplated by the Inventor

In its presently preferred (best-mode) implementation, the adaptive cartridge employs a Bürkert 6650-type piezo-diaphragm valve (PTFE body, PEEK seat, $Cv \approx 0.20$) driven at 24 V DC with a fixed 25 ms square-pulse for each micro-dose. The disposable liner is blow-moulded from PFA 450 HP (20 L nominal) and docked via a Fluoroware QCII key-coded quick-connect fitted with a Kalrez 7075 check-valve. The inline sensor stack consists of

- a Sensorex S272CD-ERP PTFE-bodied conductivity cell (cell constant = 0.1 cm^{-1}),
- a Vernier micro-ISFET pH half-cell (range 1–14, offset drift < 3 mV $week^{-1}$),
- an Elemental Scientific Modu-I™ ICP micro-cell for ionic contamination (<0.01 ppb Cu^{2+} at 10 Hz),
- a Particle Metrics NanoTrack 4400 90° laser-scatter counter (5 nm lower cutoff, 0.1 cnt mL^{-1} resolution), and
- a pair of class-A Pt100 RTDs embedded in the flow block.

All sensors are sampled at 10 Hz by an STMicroelectronics STM32H743 MCU running FreeRTOS v10.4.3; analogue inputs use dual 16-bit SAR ADCs with oversampling (effective 18 bits). Control is a PID with Smith-predictor tuned to $K_p = 0.35$, $K_i = 0.05\ s^{-1}$, $K_d = 0$, loop period 100 ms, yielding total sensor-to-valve latency ≤ 0.60 s. A 50 mL Kenics® model KMX-5 static mixer (PFA) located 80 mm downstream of the valve achieves ≥ 99 % homogenisation within 0.05 s at a 6 mL s^{-1} base-flow. Firmware commits a SEMI E143-compliant XML record for every valve pulse and transmits it via GEM E37 and OPC-UA 1.04 over 100 Base-T Ethernet. Power is supplied from the track's utility rail at 24 V DC/2 A (logic) and 48 V DC/2 A (valve driver). This configuration is the mode presently regarded as most effective for meeting the ± 0.5 % concentration window and < 0.01 ppb purity targets at sub-7 nm lithography nodes.

Alternative Embodiments

1. Valve type. In the foregoing examples the isolation valve is a piezo-diaphragm unit having a 25 ms stroke. In another embodiment the valve may be a magnetostrictive plunger, a PTFE pinch valve actuated by a voice-coil, or a digital-pressure pulse orifice. Any valve achieving an

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actuation time below 50 ms and using fluoropolymer-wetted surfaces satisfies the timing and purity constraints of the invention.

2. Sensor suite. Where conductivity and pH are unsuitable (e.g. peroxide-rich solvents), the sensor manifold can substitute an oxidation-reduction-potential (ORP) probe or an ultraviolet absorbance cell. For CMP cleans a dissolved-oxygen spot sensor may be employed. Particle detection may use either laser-scatter or differential-mobility analysis provided the lower detection limit remains ≤ 10 nm.
3. Materials of construction. While PFA and PTFE are preferred, PVDF, ECTFE or electropolished 316 L stainless steel may be used for chemistries that do not attack those materials. Elastomer seals can be Viton™, Kalrez™ 7075 or perfluoro-polyether depending on chemical compatibility.
4. Cartridge architecture. The reusable "Smart-Head" may be permanently mounted to the tool wall, with only a collapsible fluoropolymer pouch being replaced. A twin-chamber liner can provide sequential dosing of a concentrate followed by a neutraliser. Multiple liners may share a single Smart-Head through a selector manifold.
5. Mixing topology. The static mixer illustrated can be replaced by a co-axial Venturi jet, an eddy-slot turbulator machined into the dispense block, or a micromachined serpentine mixer having an internal volume below 5 mL, so long as 95 % homogeneity is achieved within 0.05 s.
6. Control algorithm. The proportional–integral–derivative loop can be replaced with a model-predictive controller or a neural-network adaptive gain scheduler. For low-cost lines, a hysteretic bang-bang controller that fires fixed-volume shots when the sensor deviates by more than a preset amount is adequate.
7. Communications. Instead of GEM-SECS and OPC-UA, the control unit may employ EtherCAT, Profinet, Ethernet/IP or an encrypted REST API, provided the per-dispense genealogy file remains available to the factory host.
8. Non-lithography use. The same cartridge architecture is applicable to post-CMP single-wafer cleans, advanced wet-etch benches (NH_4OH / H_2O_2/DI), front-end copper electro-plating suppressor control and display-glass developer dosing.
9. Safety redundancy. In high-hazard chemistries the cartridge may employ dual isolation valves in series with a leak sensor between them, or a double-containment PFA jacket tied to a vacuum leak-back line, thereby meeting SEMI S2–2018 Section 14 without altering control timing.

Any of the above alternatives may be used individually or in any technically compatible combination, and all fall within the scope of the appended claims.

End of specification

Manufacturing and Calibration

(Numbers in parentheses reference elements already defined in the Detailed Description and drawings.)

1. **Liner moulding and purification**
   The disposable liner (62) is produced by stretch-blow moulding optical-grade PFA 450 HP pellets at 340 °C into a one-piece parison. After trim and visual inspection the bottle is annealed at 260

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°C for 4 h to relieve mould stress and reduce ionic extractables. Each lot is subjected to a 24-h recirculation test with 18 MΩ cm water at 80 °C; the leachate must exhibit total metal content below 10 ppt as measured by inductively-coupled plasma mass spectrometry (ICP-MS) before release.

2. **Smart-Head body machining**
   The reusable Smart-Head (14) is CNC-machined from virgin PTFE billet; wettable internal passages are finished to an Ra < 0.2 µm and rinsed in 0.5 M HCl followed by 18 MΩ cm water. Outer faces receive a PFA over-jacket (16) heat-shrinked at 200 °C to create a gas-tight dual shield (see Fig. 11).
3. **Sensor-manifold assembly**
   Sensor bores (64) are reamed 0.05 mm oversize, flushed with nitrogen, and fitted with crush gaskets (120). The conductivity cell, pH half-cell, ionic cell and particle probe (72, 74) are torqued to 0.9 N m using a PTFE-sleeved wrench. Each manifold is leak-tested to 4 bar N_2 for 15 min and vacuum-helium tested to 1×10^{-6} mbar l s^{-1}.
4. **Valve calibration**
   Piezo valves are factory-fired 1 000 cycles in UPW to stabilise stroke. A pulse-width table (1 ms resolution) is generated by dispensing into a micro-balance; the linearity coefficient (slope ± 1 %) and dead-time constant (≤ 30 ms) are stored in on-board EEPROM with a CRC-32 hash.
5. **Sensor calibration**
   - Conductivity: three-point (0.01, 1.0, 10 µS cm^{-1}) using NIST-traceable KCl standards at 25.00 ± 0.05 °C.
   - pH: one-point 7.000 buffer + offset check at 10.000.
   - Ionic cell: six-point 0–50 ppt Cu^{2+} solution prepared gravimetrically.
   - Particle probe: PSL latex spheres (10 nm, 50 nm) in ISO-class-3 clean booth; counter gain adjusted for < 10 % error.
     Calibration constants are written to an I^2C memory inside the sensor pod; the Smart-Head MCU copies the table into its control RAM at power-up.
6. **Firmware flashing and secure ID**
   The STM32 MCU is programmed via SWD with boot-loader v1.12 and application v1.12.3; a unique 256-bit device ID and X.509 certificate are injected during flashing. Firmware images are signed; the boot loader refuses unsigned code.
7. **End-of-line functional test**
   Each assembled Smart-Head is plumbed to a recirculating UPW loop. The control firmware injects twenty 20 mL pulses while the sensor manifold logs data; acceptance limits are:

- pulse-volume error ≤ ±1 %,
- control latency ≤ 0.6 s,
- sensor noise < 0.05 µS cm^{-1} RMS.

Digital batch records are checked for SEMI E143 schema compliance.

8. **Packaging and traceability**
   The Smart-Head is nitrogen-purged, double-bagged in ISO-class-5, and packed with a desiccant

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capsule and shock logger. Each liner bottle is individually bagged and sealed with a tamper-evident cap; the RFID tag stores liner serial, chem code, and expiry. All serial numbers are logged to a MES database that maintains full device-history records for at least ten years.

9. **Field re-calibration**
   Every 90 days the firmware triggers an in-situ check: conductivity is compared against an internal UPW baseline drift; pH and ionic sensors run a two-point self-diagnostic using factory-stored coefficients. If drift exceeds 3 σ the cartridge enters QC-2 state and schedules a predictive-maintenance swap.

These manufacturing and calibration steps ensure the system meets the ±0.5 % concentration tolerance, < 0.01 ppb ionic detection, and < 0.6 s control-loop latency claimed in the accompanying claims, while providing traceable quality control compliant with ISO 9001 and SEMI F57/F104.

Example 1 (Prophetic): Adaptive-Dosing of 2.38 % TMAH Developer in a 300 mm EUV Track

The following example is prophetic; the experiment has not yet been carried out but is based on engineering models, CFD residence-time analysis, and sensor/valve response data set forth elsewhere in this specification.

Experimental set-up

Parameter	Value	Notes
Track tool	TEL **ACT-12** coater/developer clustered to ASML **NXE-3600D**scanner	Standard two-track lithography cell
Wafer lot	150 wafers, 300 mm, resist stack: ≥37 nm EUV chemically-amplified resist on 38 nm BARC	Split 75 control / 75 inventive
Chemical source (control)	Conventional 20 L PFA tank pre-diluted to 2.38 % TMAH; open-loop flow-meter dosing	“Bolus” method—5 L consumed in first 4 h

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Chemical source (inventive)	**Smart-Cartridge™** containing 25 % TMAH concentrate; valve Cv 0.2; sensor suite: conductivity + pH + T	Micro-pulse mode, target 2.38 % ± 0.02 %
Base stream	18 MΩ · cm DI water, 25 °C, 300 mL $wafer^{-1}$	Same for both arms
PID tuning	Kp = 0.35, Ki = 0.05 s^{-1}, Kd = 0	Empirically selected by Z-N method on virtual twin
Sensor sampling	10 Hz	Latency sensor→MCU 5–10 ms
Valve pulse schedule (inventive)	Six × 40 mL pulses distributed during 2 s dispense	≥95 % mix by wafer contact

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Predicted results

Metric	Control (bolus)	Inventive (Smart-Cartridge)	%-Δ
Average developer consumed / lot	**10.0 L**	**6.6 L**	–34 %
Molarity drift range (max–min over lot)	2.29–2.47 %	2.37–2.39 %	88 % tighter
CD 3σ (dense line, 13 nm, n = 5 sites × 3 wafers)	2.4 nm	1.2 nm	–50 %

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Post-develop scum defect density (>60 nm)	0.060 cm^{-2}	0.030 cm^{-2}	–50 %
Track downtime for chem change‡	30 min / 10 d	<5 min / 9 d	–83 %
Estimated yield loss (5 k die/wafer model)	1.5 % of die	0.7 % of die	–53 %

‡ Control requires nitrogen-purge tank swap; inventive uses quick-connect liner.

Narrative of operation

1. **Start-of-shift calibration.**
   The Smart-Cartridge RFID authenticates concentrate batch 25 % TMAH-2025-061; the MCU loads its conductivity-versus-temperature curve.
2. **First wafer dispense (t = 0 s).**
   Sensor reads 2.30 % equivalent molarity (0.8 % low). MCU computes a 40 mL pulse beginning at t = 0.25 s. Mixed stream reaches nozzle at t ≈ 0.55 s; second sensor sample (t = 0.70 s) reports 2.37 %.
3. **Remaining five pulses** adjust duty cycle by ±4 % as sensor converges to 2.38 % ±0.02 %.
4. **Mid-lot disturbance (virtual 1 °C track room rise).**
   Control arm drifts to 2.44 %; inventive arm compensates in <2 s with a +7 % pulse duty.
5. **End-of-lot summary.**
   MCU log shows 450 pulses, cumulative 6.6 L concentrate, and zero QC-1 deviations > ±0.5 %. GEM E143 file transmitted to host.

Expected impact

Applying the model to a 100 k-wpm foundry fab yields:

- **€3.6 M yr^{-1} chemical savings** (developer only).
- **€22–25 M yr^{-1} yield uplift** from CD and scum reduction.
- **44 h extra litho uptime** by eliminating purge-and-swap downtime.

This prophetic example demonstrates that the claimed adaptive-dosing cartridge achieves the specified ±0.5 % concentration control, material reduction, and defect improvements relative to conventional bolus methods, fully supporting the independent system and method claims.

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Example 2 (Prophetic): Adaptive Dosing of Immersion-Water Surfactant and Ionic-Trim Chelator in an EUV Scanner Loop

This example is prophetic and based on thermal-hydraulic models of an ASML immersion hood, live data from nano-particle counters, and chelator kinetics published by imec. No physical experiment has yet been run.

Experimental set-up

Parameter	Value	Notes
Scanner	**ASML NXE-3600D** (EUV, 0.33 NA)	Standard front-box DI loop, 20 L internal volume
Immersion hood flow	18 ± 2 L min^{-1} UPW at 23 °C	ASML spec
Surfactant target	**5 ppm ± 0.5 ppm** non-ionic tenside	Avoids watermark defects
Ionic budget	**≤ 5 ppt** total cations; resistivity ≥ 17.9 MΩ cm	EUV optics spec
Control arm	Bulk drum with on-demand blender; titration every 30 min	Industry practice
Inventive arm	**Two Smart-Cartridges**• Cartridge A: 2 % surfactant concentrate• Cartridge B: chelator concentrate (0.1 %)	Both feed same loop through independent valves
Sensor suite	Ionic ppb cell, nano-particle counter (≥ 10 nm), resistivity, conductivity, temperature	Sample 10 Hz

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PID target	Surf cond. proxy 0.31 µS cm^{-1}, resistivity 18.0 MΩ cm	Dead-time 0.25 s

Predicted results

Metric	Control (blender)	Inventive (Smart-Cartridge)	%-Δ
Surfactant drift (3σ over 8 h)	4.1–6.4 ppm	4.8–5.2 ppm	–72 %
Ionic excursions > 5 ppt	7 per shift	**0 per shift**	n/a
Bubble/watermark defects per wafer	0.045	**0.019**	–58 %
EUV throughput loss (re-scan delays)	1.3 %	0.4 %	–69 %
Surfactant concentrate used / 8 h	240 mL	**140 mL**	–42 %
Chelator concentrate used / 8 h	85 mL	**55 mL**	–35 %

Narrative of operation

1. **Baseline**. Ionic cell reads 3 ppt, resistivity 18.05 MΩ cm. No pulses injected.
2. **Minor ion spike (t = 1 h).**
   Particle filter swap leaks 7 ppt Na^{+}. MCU triggers Cartridge B valve: five × 0.10 mL chelator shots over 40 s. Resistivity returns to 18.0 MΩ cm; no wafer abort issued.
3. **Surfactant consumption drift (t = 2.5 h).**
   Cond. drops 0.20 µS cm^{-1} below set-point after 90 wafers. PID fires 0.08 mL pulses of Cartridge A every 30 s until cond. restored.
4. **Particle burst (t = 3.8 h, simultaneous with wafer on chuck).**
   Counter reads 32 cnt mL^{-1} (>25 limit). MCU diverts flow to waste for 2 s, injects 0.2 mL chelator, logs QC-1 alarm. Molarity of developer (running on separate cartridge) unaffected.

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5. **End of shift.** Sensor logs show 140 mL surfactant, 55 mL chelator consumed; no QC-1 limit exceeded for more than two consecutive samples. Batch records archived.

Expected fab-level impact (foundry, 140 k wpm, 5 nm EUV node)

- **€7–9 M yr^{-1} yield uplift** from watermark-defect reduction.
- **€2 M yr^{-1} scanner uptime gain** (0.9 % fewer immersion pauses).
- **€1.1 M yr^{-1} chemical savings** (surfactant + chelator).
- **CO_2 & wastewater**: 35 % less tenside discharge → ~18 t CO_2-eq. avoided.

This prophetic example supports the breadth of claims covering multi-sensor, dual-cartridge adaptive control of an immersion-water loop, demonstrating sub-second correction of both surfactant and ionic purity while the loop remains in continuous operation.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an exploded, perspective view of the Smart-Cartridge assembly showing the reusable PTFE/PFA Smart-Head, the piezo isolation valve, the multi-parameter sensor manifold, the key-coded quick-connect, and the disposable PFA liner bottle.

FIG. 2 is a fluid-path and control schematic for a single-wafer develop step, illustrating where the micro-valve injects concentrate, the 50 mL static mixer, the inline sensor cluster, and the feedback loop that closes within 0.6 s.

FIG. 3 is an electronics-and-firmware block diagram in which the sensor manifold streams data to the MCU; the MCU executes PID/AI logic, drives the valve-driver stage, and exchanges batch records with a host via GEM / OPC-UA.

FIG. 4 is a hierarchy-tier interrupt and scheduling map showing how multiple cartridges share the adaptive-logic control unit and how wafer-critical (QC-1) events pre-empt preventive-maintenance (PM-1) tasks.

FIG. 5 is a quick-connect liner-swap assembly view depicting removal of the disposable 20 L liner from its slide-in sled and attachment of a fresh liner without purging the line or halting production.

FIG. 6 is an exploded view of the sensor-manifold assembly, detailing the upper and lower fluoropolymer blocks, crush gaskets, conductivity, pH, ionic and particle probes, and the compression-nut retainers.

FIG. 7 is a computational-fluid-dynamics (CFD) simulation of the 50 mL static mixer, presenting velocity contours and tracer mixing that achieve ≥ 99 % homogenisation within 0.05 s.

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FIG. 8 is a time-series chart of valve-stroke timing versus molarity-error correction, demonstrating six 50 ms pulses that bring a –0.6 % off-spec stream back inside the ±0.05 % band well within a 2-second dispense.

FIG. 9 is a cartridge lifecycle and swap timeline spanning two weeks, highlighting routine sensor drift, an auto-flush at day 11, and a scheduled liner replacement at day 14.

FIG. 10 is a Failure-Mode, Effects & Diagnostics (FME(D)) matrix that cross-references representative failure modes with their process impacts, on-board diagnostics, firmware tiers, and automatic responses.

FIG. 11 is an EMI/EMC shielding cross-section of the Smart-Head enclosure, showing dual nested fluoropolymer shells, the N_2 purge gap, and grounding tabs that form a Faraday cage meeting IEC 61326-1 limits.

FIG. 12 is a spatial-envelope drawing of the track chemical bay, illustrating the Smart-Cartridge seated on its sled and the 200 mm vertical and 450 mm lateral clearances that prove compatibility with a standard TEL ACT-series bay.

FIG. 13 is a schematic showing all fluid and sensor connections between the Smart-Cartridge bay, the coater/developer track, the immersion scanner, and the plant UPW supply.

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