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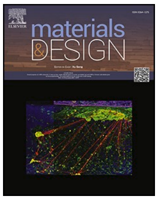

Advanced frugal methodology for accessible precision materials processing and characterization

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ABSTRACT

Frugal science offers transformative potential by democratizing access to scientific research through the replacement of specialized, high-cost laboratory instruments with accessible, low-cost alternatives. In this study, we introduce three universal advanced frugal toolkit that enable the cost-effective validation of experimental concepts across diverse engineering disciplines. We demonstrate that a repurposed household fan motor functions as an effective spin-coater substitute, exhibiting angular velocity stability that yields thin films with uniformity and morphology comparable to commercial systems. Furthermore, we establish that a common tack can be employed for nanoindentation to induce reproducible localized plastic deformation, facilitating the reliable comparative assessment of surface mechanical properties. Additionally, we show that diamond cutter-scribed guide trenches on silicon substrates successfully direct the graphoepitaxy of block copolymers, producing highly ordered nanopatterns comparable to those achieved by advanced EUV lithography. These accessible advanced frugal methods preserve critical performance characteristics while significantly lowering financial and logistical barriers, thereby supporting rapid prototyping, risk-averse decision-making, and inclusive innovation in both resource-limited and well-funded research environments.

1. Introduction

Fermi estimation [1–5]provides an engineering protocol for addressing challenges and achieving desired results when access to advanced measurement systems and data is constrained by limited resources. This pragmatic framework enables researchers to derive crucial insight using highly affordable tools [6–9]; ingenuity can surmount equipment and budget constraints. Similarly, Taguchi quality engineering aligns with achieving desired performance cost-effectively, emphasizing functional methods delivering reliable results with minimal expenditure. Deployed across scientific disciplines, these resource-optimized methodologies not only craft efficient pathways for concept validation and prototype realization but also yield scientifically valuable results and accelerate early technological development.

Global expenditures on research and development (R&D) consistently increase, reaching approximately 2.75 trillion USD in 2023 according to the OECD [10], reflecting international commitment to advancement in engineering and science. However, access to high-cost experimental equipment remains a persistent barrier for many researchers in the scientific community. While various initiatives enhance resource efficiency, policies haven't fully alleviated the financial burden due to administrative obstacles and the centralization of available equipment in specific institutions or regions. This challenge acutely affects researchers with limited budgets, particularly early-career scientists, but also impacts well-funded institutions by impeding rapid prototyping and preliminary feasibility testing. Consequently, the need

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for strategies enabling quick, low-cost validation is crucial not only for broadening scientific access but also for optimizing resource allocation, reducing investment risk, and ultimately increasing the likelihood of success by avoiding substantial sunk costs [11–16].

Recent trends in scientific research have increasingly emphasized the 'democratization of science' and 'low-cost laboratory automation' to accelerate discovery cycles and broaden participation [21,26]. Despite these advancements, the prohibitive capital cost of high-precision instrumentation remains a significant barrier, particularly for resource-limited institutions and early-stage proof-of-concept studies [44]. This economic constraint often stifles innovation by limiting the ability to perform rapid prototyping and feasibility testing [45]. In this context, the principles of 'Frugal Engineering' [46]—which focus on reducing complexity and cost without compromising core functionality—offer a strategic pathway to overcome these hurdles. Following this paradigm, advanced frugal science [17–21] implements this strategic pathway by creating functional scientific tools from low-cost, easily accessible materials. This approach embodies the resourceful, do-it-yourself (DIY) strategies [22–25] scientists already use to overcome barriers posed by expensive instruments and limited access. It represents an innovative design that enables valuable scientific inquiry where traditional methods are impractical or unavailable. Notable examples, such as paper centrifuges [26,27], triboelectric X-ray devices [28], foldable paper microscopes [29,30], and bubble wrap assays [31–33], demonstrate how affordability and practicality drive scientific innovation. These advancements [34–36] not only support resource-limited early-career researchers in accessing cutting-edge research but are also efficient in demonstrating feasibility to optimize resource allocation and increase the probability of investment success [37,38].

In this study, an innovative, practical, and low-cost technological strategy that implements the principles of advanced frugal innovation (AFI) is proposed. Universal toolkits have been developed to validate experimental concepts economically without expensive instrumentation, thereby opening opportunities for advanced scientific measurements across disciplines. This approach facilitates the creation of measurement and processing strategies that benefit not only resource-limited researchers but also well-funded ones to minimize risk through preliminary feasibility assessments that optimize investment decisions. Experimental demonstrations include methods commonly employed across a broad range of engineering and scientific disciplines, such as: 1) the fabrication of precisely micro-patterned thin films utilizing a commercially available fan motor as an economical alternative to conventional spin-coating equipment; 2) the performance of nano-indentation measurements using the sharp tip of a common tack as a cost-effective substitute for expensive nano-indentation instruments; and 3) the creation of nanoscale line patterns through direct substrate scratching with a diamond cutter, providing an accessible alternative to high-cost extreme ultraviolet (EUV) lithography systems. These strategies yield significant cost savings and streamline operations, enabling the efficient validation of initial experimental concepts regardless of funding availability. By matching the performance of traditional high-precision methods, the innovative techniques optimize resource utilization, while the multidisciplinary AFI approach simultaneously creates valuable opportunities for resource-constrained early-career scientists and facilitates preliminary feasibility assessments for well-funded researchers, thereby supporting cost-effective investment decisions.

2. Experimental section

2.1. Thin film formation and patterning using a commercial fan motor

To replicate the centrifugal force mechanism of a conventional spin coater, a commercial fan motor (Hanil, Model HM-3000) was mounted in an inverted vertical configuration. Glass substrates (2.5 cm × 2.5 cm) were secured onto a custom-fabricated Teflon holder to minimize axis misalignment and vibration during rotation. Photoresist AZ 4620 (MicroChemicals GmbH) was dispensed (100 μL) at the center of each substrate. Spin coating was performed at three motor speed levels (i, ii, iii), corresponding to approximately 1650, 1700, and 1750 rpm rotational speeds, respectively. An infrared tachometer (IR tachometer) was employed to monitor the real-time rotation speed. Reflective tape was affixed to the substrate to enable precise RPM calculation via reflected pulse signals. The measured speeds remained within a stability margin of ± 10 rpm. Following spin coating, substrates were soft-baked on a hot plate at 100 °C for 1 min to evaporate the solvent and stabilize the resist. The resulting film thickness ranged from approximately 10 to 20 μm, depending on the spin speed, as confirmed by 3D surface profilometry [39]. Photolithographic patterning was conducted using a mask aligner (Midas Systems, MDA-400 M) in contact exposure mode. The resulting patterns—comprising linear, grid, and circular geometries defined by the photomask—were first examined using an optical microscope (Olympus BX53M), followed by quantitative analysis of cross-sectional profile, height, and surface uniformity using a 3D optical profiler (Keyence, VHX-600). The morphology, uniformity, and resolution of the AZ 4620 thin films and patterns formed via this fan-assisted spin coating method were comparable to those obtained using conventional spin coaters. Furthermore, compatibility with standard photolithographic processes was fully retained.

2.2. Nano-indentation using a commercial tack

A standard stainless steel thumbtack (tip radius ~ 10 μm) was mounted vertically on a manually controlled compression stage to evaluate local mechanical properties. A digital force gauge (AND Instruments, FG-5000A) was connected to monitor the applied load in real time. The thumbtack was aligned to apply a normal force perpendicular to the sample surface. The test samples were fabricated by casting poly (methyl methacrylate) (PMMA, Sigma-Aldrich, Mw ~ 120,000) onto a silicon wafer, forming a flat film. The samples were air-dried at room temperature for 10 min and then soft-baked at 100 °C for 2 min to remove residual solvent. Indentation tests were performed by applying a constant load of 15 N for 10 s. Indentation was repeated at five positions on the same sample to ensure reproducibility. Surface deformation was characterized using a 3D laser confocal optical profiler (Keyence, VHX-600). Cross-sectional profiles were analyzed to quantify maximum indentation depth, residual pit diameter, and deformation radius. After horizontal leveling, all profiles were aligned to a common baseline using software-based surface correction for comparative analysis. A commercial nanoindenter (Anton Paar, NHT3) was employed for benchmarking. Indentation was performed on the same PMMA samples under varying loads of 10, 20, 30, 40, and 50 N. Load–displacement (L–D) curves were obtained to extract depth of penetration and stress–strain characteristics.

2.3. Graphoepitaxy of block copolymers via diamond Cutter-Scribed substrates

Silicon wafers were cleaned in piranha solution (3:1H_2SO_4:H_2O_2) for 15 min, rinsed thoroughly with deionized (DI) water, and dried under nitrogen gas. Surface patterning was performed by vertically scribing the wafer using a commercial diamond cutter (LK labkorea, RUDS68) under controlled pressure, forming parallel trench arrays with widths of approximately 1–2 μm. The scribing process produced regularly spaced linear trenches, constituting mechanically guided surface features [40–43]. Notably, subsurface cracks generated during the scribing process played a dominant role in guiding the self-assembly of block copolymers (BCPs), acting as defect-based graphoepitaxial cues in the absence of conventional topographical lithographic templates. These mechanically induced defects provided localized strain fields and surface anisotropy that promoted domain alignment in BCP films. Two types of PS-b-PMMA block copolymers (44 k-45 k and 25 k-26 k, Polymer Source Inc.) were dissolved separately into toluene at a concentration of 1 wt%. Each solution was spin-coated onto the scribed wafers at 3000 rpm for 30 s. Thermal annealing was then carried out in a vacuum oven at 180 °C for 4 h to induce microphase separation. After annealing, the films were exposed to ultraviolet (UV) light ($\lambda = 254$ nm) for 30 min and immersed in glacial acetic acid for 2 min to remove the PMMA domains selectively. The resulting nanostructures were characterized by field-emission scanning electron microscopy (FE-SEM, Hitachi S-4800). Highly ordered lamellar arrangements were observed within and around the scribed trench regions. In particular, the 25 k–26 k BCP exhibited registry between its natural domain spacing and the trench width, enabling vertically aligned domains inside the trenches and extending into adjacent areas, demonstrating effective uniaxial graphoepitaxial alignment.

3. Result and discussion

3.1. *Strategic imperative and framework of advanced frugal science in modern R&D*

Fig. 1a shows a schematic illustration of the setups for both a high-tech lab and an advanced frugal tech lab. High-tech labs typically achieve exceptional accuracy and performance by utilizing sophisticated components such as high-precision instruments, specialized modules, and custom hardware. Conversely, advanced frugal tech labs leverage readily available, mass-producible, and low-cost tools, grounding their operation in fundamental scientific principles and creative problem-solving. While the accuracy and performance of frugal technologies may not perfectly equate to those of their high-tech counterparts, frugal labs unequivocally demonstrate the capability to execute similar functions with high fidelity. The strategic imperative for advanced frugal technologies is further underscored by current global R&D expenditure trends. Fig. 1b illustrates the continuous rise in global R&D spending, both in absolute terms and as a percentage of GDP. Despite this overall increase, resource constraints persist for many, particularly among early-career researchers, thus impeding universal access to high-tech laboratories. Frugal science methodologies offer a solution by enabling early-career researchers to significantly reduce their operational costs. Moreover, the need for frugal technologies extends beyond resource-constrained individuals. Even in well-funded research or institutional settings, a critical need for strategic, evidence-based investment to ensure successful and efficient resource allocation is recognized. As vividly demonstrated by the conceptual model presented in Fig. 1c, project risk is profoundly sensitive to the sunk cost ratio—the proportion of non-recoverable expenditure within the total budget. Should this ratio exceed 40 %, even a single high-cost experimental failure can precipitate a project's entry into a ‘danger zone’, potentially dealing a fatal blow to the entire research endeavor. This inherent vulnerability, affecting both nascent and established researchers alike, underscores the strategic necessity of developing risk-averse preliminary validation methodologies. The multi-criteria analysis depicted in Fig. 1d further clarifies the strategic advantages inherent in both advanced frugal and high-tech paradigms. High-tech systems offer superior 'precision', excelling in areas such as atomic-level resolution or ultra-high accuracy in measurements. Conversely, the advanced frugal approach unequivocally excels in dimensions crucial for agile, early-stage, and resource-constrained research. Key advantages include 'cost effectiveness' due

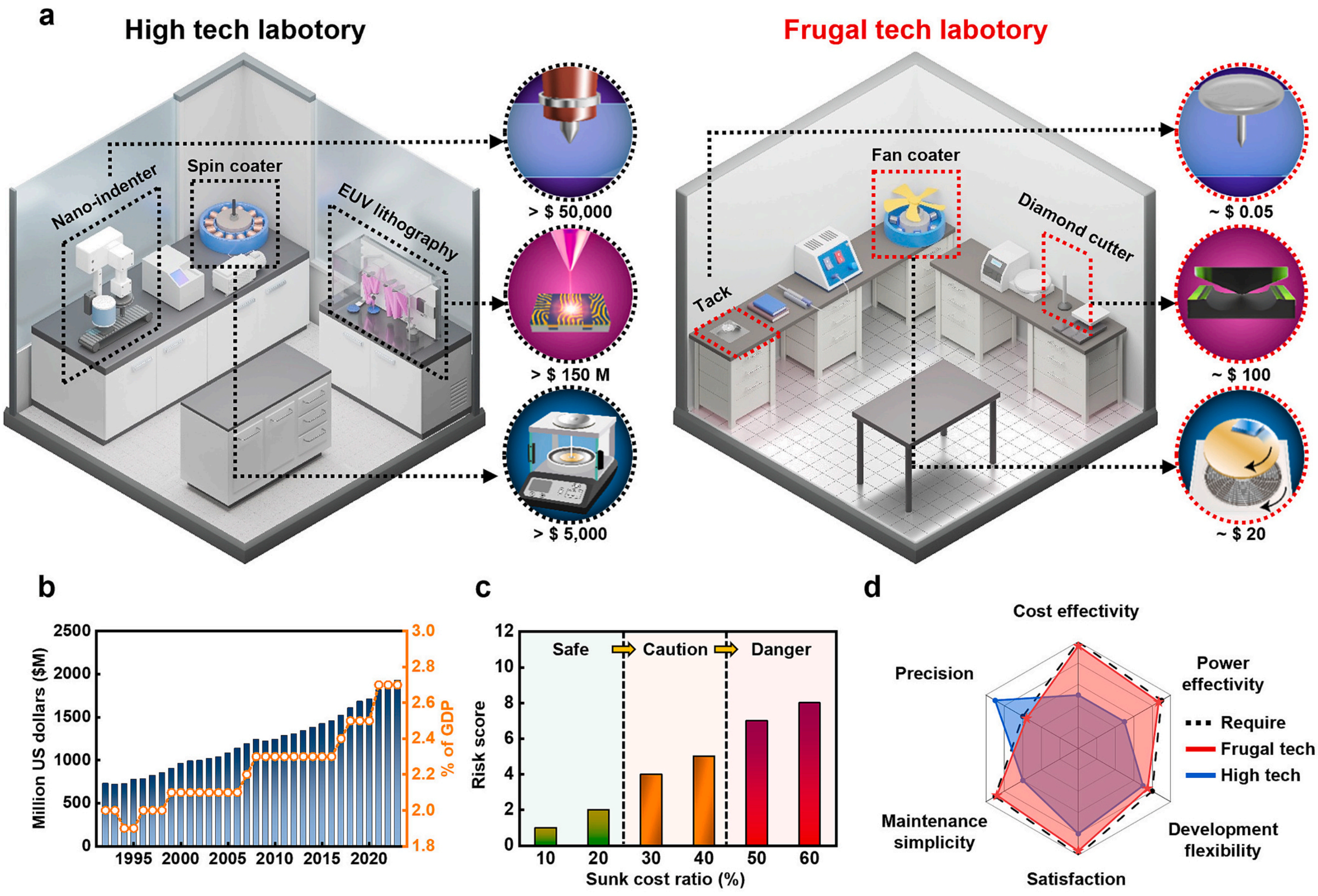

Fig. 1. (a) Schematic comparison between a high-tech laboratory and a frugal-tech laboratory. High-tech setups utilize specialized, high-precision equipment, while frugal labs operate using low-cost, widely accessible components grounded in fundamental principles. (b) Global R&D spending trends. (c) Conceptual model showing how high sunk cost ratios can significantly increase project risk and failure. (d) Multi-criteria analysis comparing high-tech and frugal-tech approaches.

to minimal resource expenditure, 'maintenance simplicity' owing to fewer complex and proprietary components, and high 'deployment flexibility' across diverse setting conditions. This comprehensive analysis substantiates that advanced frugal science transcends mere cost-cutting; rather, it represents a scientifically rational and strategically imperative approach designed to enhance research efficiency, broaden accessibility to scientific inquiry, and optimize overall project success by mitigating financial risk. The following sections will provide empirical validation of this principle through three distinct experimental demonstrations, each targeting a fundamental and broadly applicable laboratory process.

3.2. Cost-effective thin film fabrication via commercial fan-based spin coating

The precise fabrication of uniform thin films is a cornerstone in various fields, ranging from materials science to optical and electronic devices. Spin-coating, a widely adopted strategy for thin film fabrication, relies on the intricate fluid dynamics of a viscous liquid on a rapidly rotating substrate. The final thickness (t) of thin film is theoretically governed by the relationship,

$t \propto \omega - 1/2.$

where ω is the angular velocity.

From this relationship, the uniformity and quality of the resultant film are profoundly sensitive to the stability and consistency of this rotational speed. Our proposed advanced frugal approach ingeniously replaces the expensive, precision-engineered motor of a conventional spin coater with a commercially available fan motor (Fig. 2a). This novel substitution aims to significantly lower the financial and logistical barriers to advanced thin-film research by enabling fabrication with readily available components, even when high-cost spinners capable of precise control are not accessible. An in-depth characterization of the rotational dynamics of the commercial fan was first conducted to rigorously validate its scientific viability. This was achieved through a simple, yet robust, optical method involving laser reflection off a rotating element, as shown in Fig. 2b, allowing for real-time and continuous monitoring of the angular velocity. Consequently, while a specific initial time is required for the commercially available fan motor to reach the target

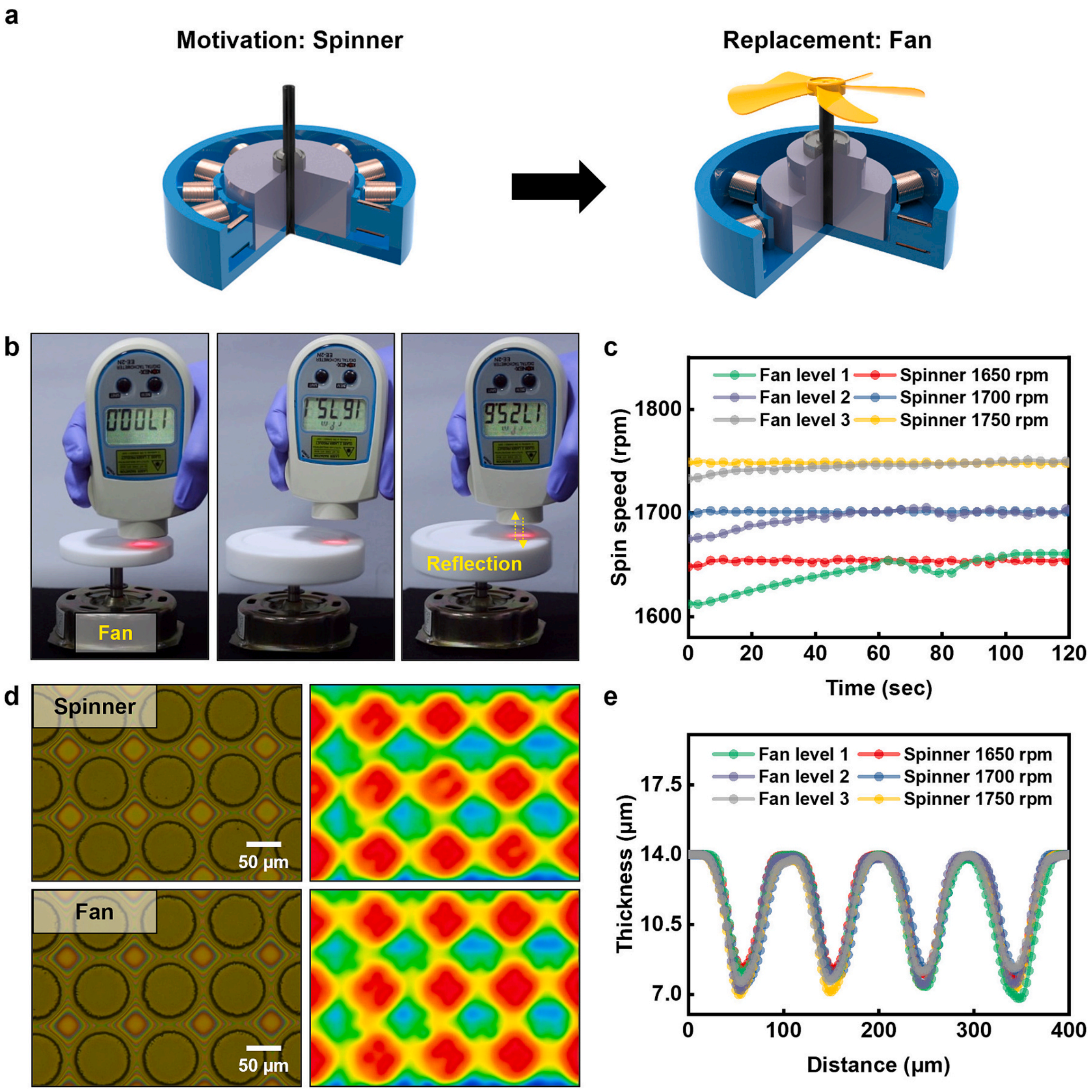

Fig. 2. (a) Comparison between a conventional spin-coating system and a frugal setup using a vertically mounted commercial fan motor. (b) Setup for real-time angular velocity measurement using laser reflection and a digital tachometer. (c) The rotational speed profile shows stable operation after the initial ramp-up. (d) Optical and 3D profiler images of thin films fabricated via fan-based and commercial spin coaters show comparable uniformity. (e) Thickness profiles confirm consistent film morphology across both methods.

rotational speed, a stable angular velocity exhibiting speed uniformity comparable to that achieved by precision spin coaters is subsequently maintained (Fig. 2c). This demonstrated rotational stability provides the indispensable physical basis for achieving uniform thin film fabrication. For experimental validation of the methodology, spin-coating was then performed using a typical polymer solution through both methodologies (See details in Experimental Section). Microscopic analysis of the resulting film reveals that the fan-based method consistently produces precisely patterned films that are morphologically indistinguishable from those created by a conventional spinner, thereby confirming the scientific efficacy of the advanced frugal methodology (Fig. 2d, left). Both methods yield well-defined circular patterns with consistent 3D morphology, as validated by 3D profiler measurements (Fig. 2d, right), indicative of uniform film formation across the substrate. This compelling qualitative observation is further substantiated by rigorous quantitative profilometry (Fig. 2e). The consistency in thickness periodicity serves as a critical proof-of-concept that accessible household appliances can maintain the angular velocity stability required for precision thin-film fabrication, thereby providing the reliable precision necessary for risk-averse decision-making. Although minor transient fluctuations were observed during the initial start-up phase, real-time monitoring confirmed that the rotational speed stabilized within a few seconds, subsequently maintaining a steady state suitable for standard spin-coating processes. This effective process control yielded films with thickness distributions quantitatively comparable to the commercial benchmark, demonstrating that the complex interplay of centrifugal force, viscous drag, and solvent evaporation can be effectively controlled even with a rudimentary setup. While the current system is effective, the future adoption of motor prototypes with pre-verified rotational performance is anticipated to further enhance the reliability of this accessible manufacturing method.

3.3. *Accessible mechanical characterization using a household tack as an indenter*

Nano-indentation is a key technique for quantitatively assessing localized mechanical properties such as hardness, elastic modulus, and creep. Assessment is achieved by precise measurement of the applied load and resulting indenter penetration depth. An advanced frugal alternative is presented, which utilizes a common household tack as the indentation tool instead of the expensive displacement probes employed in commercial nano-indenters (Fig. 3a). The scientific premise

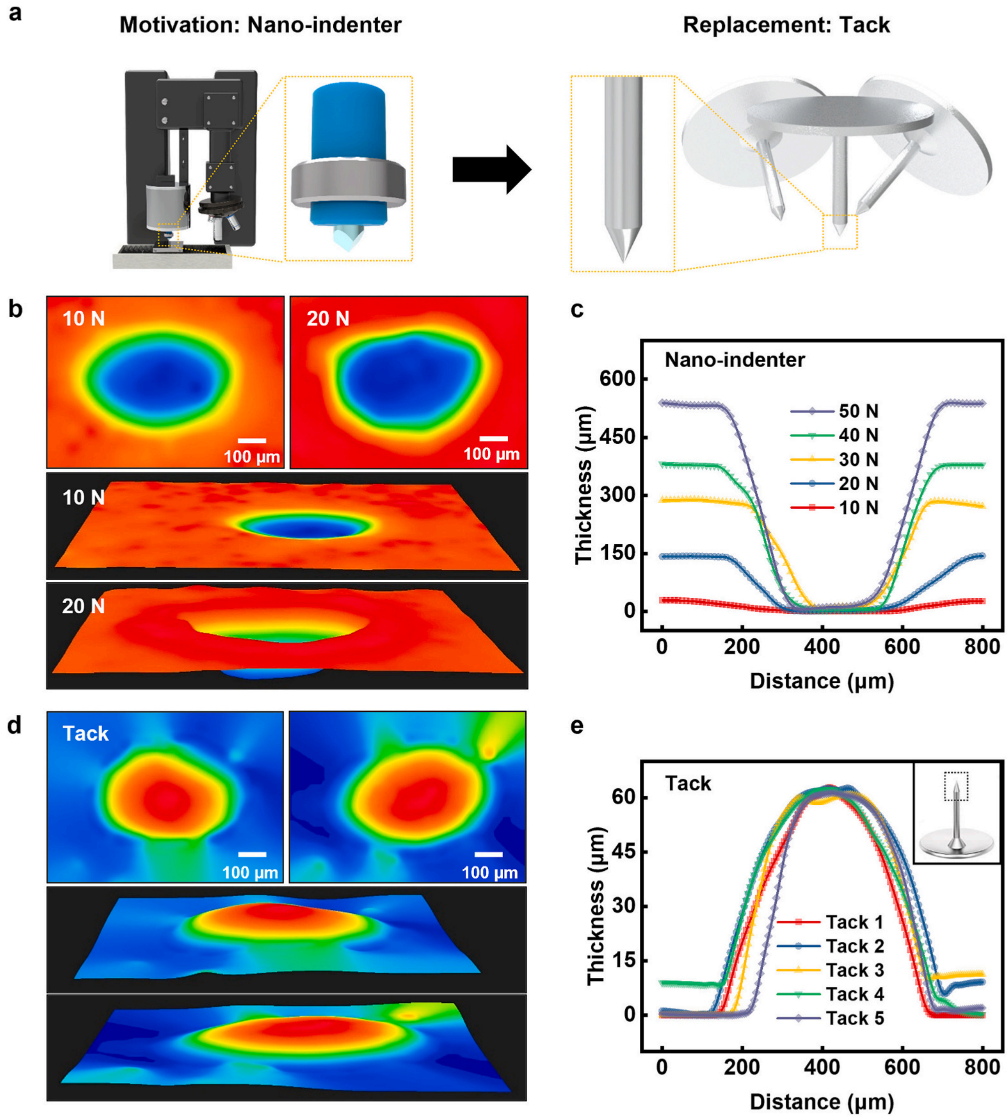

Fig. 3. (a) Schematic of the nano-indentation setup using a common tack on a manual compression stage. (b) 3D surface profile of PMMA indented by a commercial nanoindenter. (c) Depth profiles obtained under varying loads using the nanoindenter. (d) Surface deformation profile resulting from tack-based indentation. (e) Overlay of repeated tack indentations demonstrating excellent repeatability and mechanical consistency.

underpinning this approach is that consistent localized plastic deformation can be reliably induced by a readily available sharp tip of a tack, even without absolute force calibration. While precise control of force magnitude is challenging, a repeatable effective force enables a robust comparative probing of mechanical responses across different samples or surfaces. Fig. 3b shows the 3D surface profile of a material after deformation induced by specific loads (e.g., 10 N, 20 N) applied with a commercial nano-indenter. Thickness variations observed in this 3D profile are precisely represented as quantifiable indentation depth profiles in Fig. 3c. Information obtained from these profiles provides insights into elastic and plastic deformation characteristics. The alternative frugal method utilizing a tack aims to provide similar essential insights for localized surface property analysis. The scientific utility and reliability of the simplified method hinge critically on its repeatability. As shown in Fig. 3d, topographical profiles of indentations induced by the tack are consistently well-defined and exhibit localized deformation areas. Furthermore, repeated indentations performed under identical conditions yield remarkably consistent depth profiles, as compellingly demonstrated by the precise overlapping of multiple curves in Fig. 3e. Exceptional repeatability indicates the effective stress applied at the tack tip remains highly consistent across successive trials. This mechanical reliability, visually confirmed by the tight overlapping of depth profiles in Fig. 3e, demonstrates that the system achieves the precision necessary for reliable comparative screening, thereby aligning with the goal of lowering barriers to high-fidelity mechanical characterization. While viscoelastic effects such as creep are inherent to polymeric materials, the advanced frugal indentation method minimizes time-dependent variations by maintaining a fixed dwell time, thereby focusing on comparative hardness assessment under constant loading conditions. Consequently, this strategy serves as an effective tool for the rapid mapping of mechanical property uniformity, preliminary screening of relative hardness in material formulations, and the assessment of processing parameter impacts on material rigidity.

3.4. Sub-micron graphoepitaxy enabled by diamond-scribed templates for directed BCP assembly

Achieving precisely ordered arrangement and feature resolution in

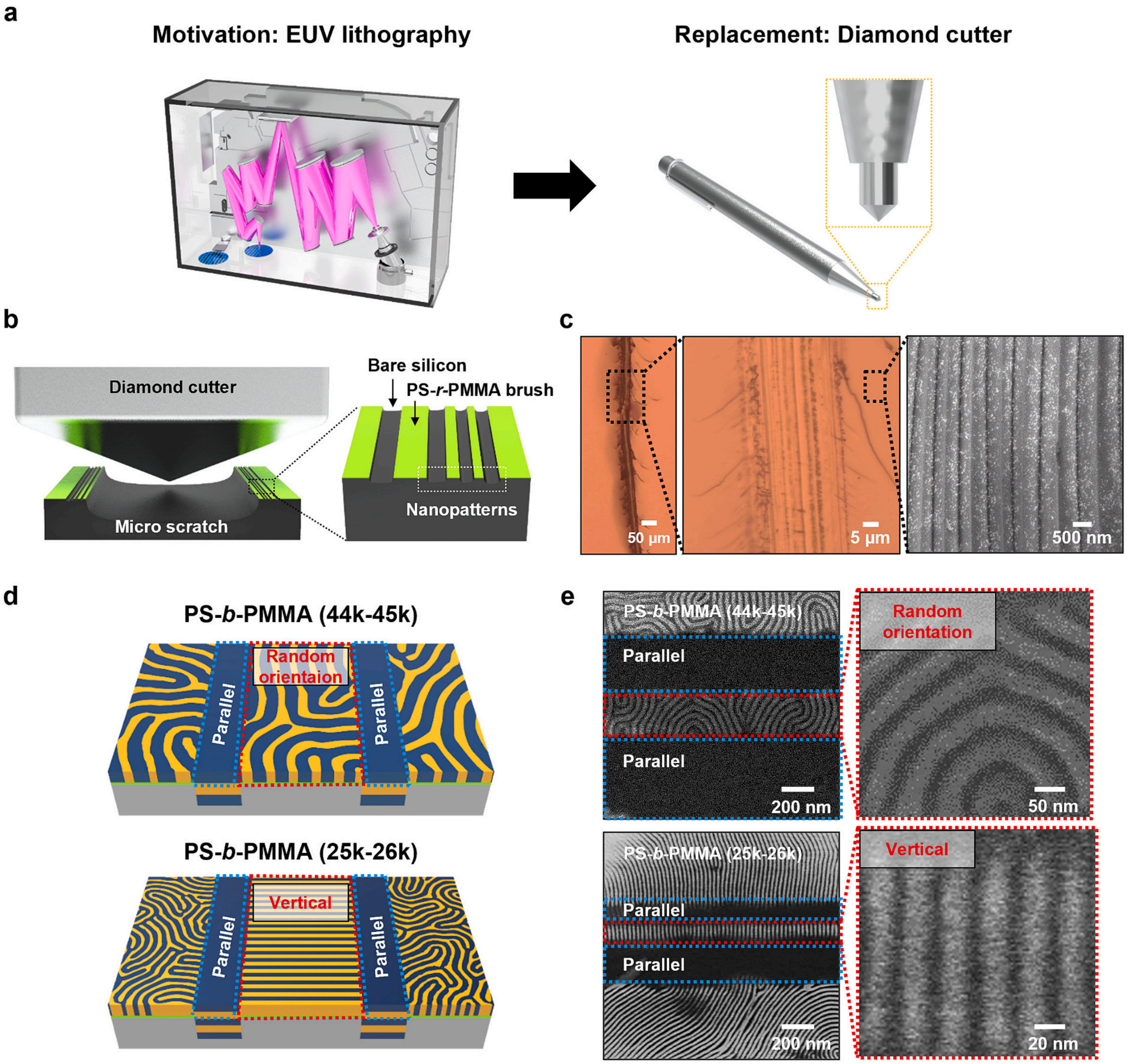

Fig. 4. (a) Overview of the BCP alignment strategy using mechanically scribed guide patterns. (b) Image of a diamond cutter used to create micro-scale trenches on silicon wafers. (c) SEM image showing precisely defined trenches formed by manual scribing. (d) Diagram of PS-b-PMMA block copolymer alignment directed by these guide structures. (e) High-resolution SEM images confirming well-aligned lamellar domains within and beyond the scribed regions, demonstrating effective graphoepitaxy.

nanoscale patterns below 50 nm remains a central challenge in advanced nanotechnology and high-performance electronic device manufacturing. Extreme Ultraviolet (EUV) lithography has attracted significant attention as a methodology capable of fabricating ultra-fine patterns (5 ~ 10 nm), despite its ultra-high cost. In this regard, block copolymers (BCPs) are materials composed of different polymer blocks that spontaneously form regular, nanometer-sized patterns (5 ~ 10 nm) over large areas in parallel through self-assembly, making them a useful strategy for nanoscale pattern formation. However, achieving global alignment and directional control for practical BCP nanopatterns is not spontaneous; it requires topographical guide patterns with sub-micrometer widths, which typically rely on complex, high-cost lithography techniques such as EUV lithography or advanced photolithography, demanding significant capital and infrastructure. Here, we present a frugal yet scientifically potent alternative that replaces micro-guide patterns (300 nm ~ 3 μm) produced by advanced lithography with templates mechanically defined by a diamond cutter (300 nm ~ 3 μm) (Fig. 4a). By utilizing these mechanically scribed trenches to precisely guide the self-assembly of poly(styrene-block-methyl methacrylate) (PS-b-PMMA), we aim to achieve nanoscale ultra-fine features comparable to those obtained with EUV lithography. The micro-scale guide patterns are meticulously formed by physically scratching a bare silicon substrate with a readily available diamond cutter (Fig. 4b). The superior efficiency and precision of this mechanical scribing technique are clearly confirmed by high-resolution scanning electron microscopy (SEM) images in Fig. 4c. These images show the formation of precisely defined and uniform trenches, demonstrating the feasibility of creating guide patterns at the micro- and sub-micron scale with remarkable control, without relying on specialized lithography equipment. This graphoepitaxy process profoundly leverages the physical confinement provided by these mechanically scribed trenches to overcome the inherent activation energy barrier for forming a single, desired orientation of the BCP domains. For the specific purpose of feasibility screening, strict global uniformity of the trench geometry is not a prerequisite. The primary function of the manual scribe is to generate localized confinement fields to verify the self-assembling capability of the block copolymer. Successful alignment within these regions serves as a sufficient indicator of material feasibility, thereby justifying the subsequent allocation of resources for high-precision lithography. When subjected to thermal annealing within these predefined guides, the two different molecular weight BCPs (PS-*b*-PMMA (44 k-45 k) and (25 k-26 k)) exhibited a distinct contrast depending on their commensurability with the trench dimensions (Fig. 4d). The resulting high-magnification SEM images provide unequivocal and compelling proof of the proposed strategy (Fig. 4e). While the higher molecular weight BCP (44 k-45 k) showed a random orientation of lamellar domains due to the mismatch between the guide width and the BCP period, the 25 k-26 k BCP successfully achieved highly ordered patterns. Specifically, for the 25 k-26 k BCP, where the guide pattern width is commensurate with the BCP natural periodicity, the lamellar domains are observed to align perpendicularly not only to the substrate surface but also parallel to the trench walls. This observed domain registry is primarily driven by geometric confinement, where physical boundaries direct the self-assembly process. This distinct alignment confirms that the manual scribing process effectively creates the necessary boundary conditions for graphoepitaxy, independent of complex surface energy modification treatments. While the underlying physical principles remain valid, scalability to industrial high-precision applications is subject to practical constraints such as operator dexterity in manual scribing and hydrodynamic edge effects in simplified spin coating. Therefore, these toolkits are best suited for rapid, small-batch concept validation, serving as a screening tool to preemptively identify optimal geometric parameters and minimize trial-and-error in subsequent high-cost processes. This research presents a viable method for creating ordered nanoscale patterns without expensive, advanced lithography equipment, significantly expanding the accessibility of nanofabrication technologies. Collectively, the three methodologies—the fan motor spin coater, the tack nanoindenter, and the diamond scribe lithography—establish a powerful proof-of-concept for the advanced frugal science approach. A thorough cost quantification of the components used across all three frugal toolkits is presented in the Bill of Materials Table (Table S1) in the Supplementary Information, demonstrating the orders-of-magnitude cost reduction compared to their commercial counterparts. Future work will focus on establishing standardized calibration protocols and expanding the compatibility of these frugal toolkits to ensure broader inter-laboratory reproducibility beyond the initial feasibility demonstrated in this study.

4. Conclusion

In this study, we introduced an innovative and practical technological strategy based on advanced frugal science, addressing the challenges of high costs and limited access to advanced experimental tools. By creating universal toolkits for economical concept validation, our method greatly expands possibilities for advanced scientific measurements across various fields. We demonstrated this through three key experiments. 1) We successfully made precisely micro-patterned thin films using a common fan motor, showing it's an affordable and effective alternative to expensive spin-coating. 2) We performed nanoindentation measurements with a simple tack, proving a cost-effective way to gauge localized mechanical properties with high consistency. 3) We created micro-scale guide patterns by directly scratching substrates with a diamond cutter. This demonstrated an accessible alternative to the high-cost lithography systems often needed for block copolymer self-assembly, and consequently, this method enables the formation of nanoscale patterns comparable to those achieved with EUV lithography. These advanced frugal methods not only save significant costs and streamline work but also yield results comparable to traditional high-precision techniques. Ultimately, this approach empowers early-career scientists with limited resources to conduct cutting-edge research and helps well-funded researchers make informed investment decisions through preliminary feasibility checks, thereby optimizing resource use in scientific and technological advancements. Beyond the immediate research impact, the defining characteristics of this methodology—cost-effectiveness and simplicity—extend its utility to the realm of scientific literacy and public outreach. Furthermore, the inherent low cost, safety, and simplicity of the proposed methodologies render the systems ideal as low-budget teaching kits for undergraduate laboratory courses and for integration into remote laboratory frameworks, substantially contributing to the accessibility of practical scientific education.

CRediT authorship contribution statement

Jun Hyun Park: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Ho Jun Jin:** Visualization, Writing – original draft. **Simon Kim:** Formal analysis, Visualization. **Su Eon Lee:** Methodology, Visualization. **Young Chun Ko:** Investigation, Formal analysis, Methodology. **Jang Hwan Kim:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Validation. **Bong Hoon Kim:** Validation, Project administration, Investigation, Funding acquisition, Conceptualization, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.matdes.2026.115525.

Data availability

Data will be made available on request.

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