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An In-Depth Review of Models Used to Optimize Electron Beam Lithography Processes

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Abstract: Electron beam (EB) lithography represents a fundamental technique in the semiconductor industry, involving the precise focus of electron beams onto silicon wafers to fabricate integrated circuits (ICs). This process leverages a suite of essential components, including an electron cannon, blanking electrode, deflection electrode, multiple electron lenses, and dedicated control circuits for each of these constituent parts. However, the challenge arises from the occurrence of crucial dimension overshoots during the lithography process, leading to a degradation in the quality of the resulting ICs. This deterioration stems from reduced re-exposure of chip regions, heightened beam currents, and an increased frequency of electron flashes. To address these critical issues, researchers have introduced a diverse array of optimization models, each possessing distinct qualitative and quantitative performance characteristics. The task of selecting the most suitable model for a specific application can be daunting, given the inherent variability in the operational properties of these models. To alleviate this uncertainty, the present work delves into the limitations specific to deployment, highlights functional advantages, elucidates application-specific intricacies, and outlines future research directions within the context of EB lithography optimizations. This comprehensive exploration has revealed the superiority of bioinspired models over traditional linear modeling techniques, particularly in the realm of real-time deployments. Unlike their predecessors, these bioinspired models target stochastic optimality in electron beam design, thereby concurrently enhancing both the quality and speed of wafer imprinting sets. To facilitate the decision-making process, this article undertakes a comparative analysis of various models, considering criteria such as crucial dimensions, throughput, accuracy, computational complexity, and deployment costs. In light of this discourse, researchers are empowered to make informed choices regarding the selection of models that align with the specific performance requirements of their applications. Furthermore, this paper advocates for the adoption of a novel metric, termed EB Lithography Optimization Metric (EBLOM), which amalgamates multiple performance metrics to evaluate the real-time performance of models in a holistic manner. The incorporation of EBLOM allows researchers to identify models that excel in diverse usage scenarios, offering enhanced efficiency and performance within the constraints of performance-specific limitations.

Keywords: *Electron, Beam, Lithography, Currents, Flashes, Exposure, EBLOM, Accuracy, Throughput, Critical Dimensions, Cost, Complexity*

1. Introduction

The process of crafting a robust Electron Beam (EB) Lithography model is a multifaceted endeavor that spans various domains. It encompasses the orchestration of numerous facets, including beam deflection control, beam blinking management, motor control, stage supervision, laser inference systems, and other models tailored to specific deployment scenarios. The seamless integration of a diverse array of Machine Learning Models (MLMs) into the EB test bed is imperative, enabling the efficient operation of a multitude of interfaces. Amidst the intricate interplay of these components and their intricate relationships, a prototypical EB Lithography Model emerges [1].

The control of beam blinking and deflection interfaces necessitates the utilization of high-speed data processing techniques, under the stewardship of either a linear or bioinspired processing model. In addition to their primary functions, these models yield control signals that govern the actions of staging apparatuses, thereby facilitating adjustments in various motor and laser inference block operations. It is pertinent to note that these high-speed processes may inadvertently amplify critical dimensions, leading to a detriment in wafer quality. To mitigate these challenges, researchers have proffered a spectrum of methodologies aimed at optimizing beam currents, enhancing the periodicity of electron flashes, and optimizing the re-exposure of specific areas.

Within the confines of this discourse, an exhaustive survey of these models [2, 3, 4, 5, 6] ensues, exploring their potential future horizons, intrinsic constraints tied to deployment scenarios, nuanced benefits in specific

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contexts, and subtleties germane to distinct applications. This comprehensive assessment serves as an invaluable resource, empowering researchers to discern the most suitable models tailored to their unique use cases, characterized by distinctive features.

Furthermore, Section 3 of this article undertakes a rigorous evaluation and comparative analysis of the various methods, employing a spectrum of metrics encompassing computational complexity, accuracy, throughput, crucial dimensions, and deployment costs. This analytical section follows the preceding discussion, offering a structured framework for researchers to make informed choices regarding model selection.

In a bid to further enhance the efficacy of model assessment, this section also advocates for the adoption of a novel metric, the EB Lithography Optimisation Metric (EBLOM). This metric amalgamates an array of evaluation indicators, streamlining the process of identifying the most suitable models for a diverse array of use cases. By harnessing EBLOM, researchers gain the capacity to pinpoint models that exhibit superior real-time performance levels within the constraints specific to their deployment scenarios.

2. Literature Review

Researchers have developed a multitude of models aimed at enhancing the intricacies of electron beam lithography. Each model exhibits unique internal operational characteristics. The primary objective articulated in [1] revolves around the utilization of electron beam lithography to facilitate the transfer of nanopatterns while concurrently optimizing the dosage of the electron beam. A comprehensive analysis was undertaken to ascertain the most efficacious approach for harnessing varying thicknesses of PMMA e-beam resist in augmenting lithographic properties. This research has culminated in the achievement of sub-80 nm circular dot patterns characterized by impressive aspect ratios and unparalleled resolution. The fabrication of VLS nanostructures was accomplished through the adept utilization of the lift-off technique to engineer an Au template. Additionally, the crystallography of TiO2 nano islands, meticulously arranged on an Au template, underwent scrutiny via the X-ray diffraction technique. Notably, the nano islands exhibit a hexagonal morphology.

The foremost determinant influencing the resolution of electron beam exposure, commonly referred to as the proximity effect (PE) [2], commands profound attention within this study. Employing electron scattering Monte Carlo simulations, the investigation delves into the intricate intricacies of the proximity effect. The study introduces effective methodologies for rectifying the proximity effect, acknowledging the multifaceted factors that influence it, encompassing process conditions, pattern design, size, and packing density. The substantiation for these findings is fortified by both theoretical underpinnings and empirical experimentation. It is imperative to note that the mitigation of proximity effects transcends the capabilities of software algorithms; instead, it hinges upon the manipulation of process conditions and the refinement of mask design. The confluence of mask design, process optimization, and proximity effect correction software presents a viable avenue for mitigating the adverse effects of the proximity effect.

Prominent organizations operating within the integrated circuit domain grapple with challenges of throughput and process variation while navigating the transition towards 1D gridded designs, instrumental in enabling sub-20nm node scaling [3]. The innovative realm of Hybrid Lithography (HLith) emerges as a viable solution, amalgamating the strengths of disparate single-layer fabrication techniques. Researchers proffer an inventive approach to judiciously distribute cuts to 193i or E-Beam processes, tailoring the cut distribution as necessitated by the circumstances. The researchers conceptualize the redistribution challenge as an Integer Linear Programming (ILP) problem with clearly delineated parameters. The theoretical constructs are operationalized through the development of an algorithm that harnesses prohibited patterns in the optical simulation. Robust validation procedures affirm the efficacy of this approach. The paradigm of cut redistribution stands as a novel technique poised to bolster throughput efficiencies via empirical experimentation, ultimately curtailing the incidence of Electron Beam Lithography (EBL) in less densely populated layers, thereby effecting a reduction in manufacturing costs.

The optimization of Electron-Beam Lithography (EBL) for the fabrication of microwave circuits witnessed a paradigm shift through the application of genetic and simplex-downhill (GSD) algorithms [4]. The inherent complexity of submicrometric structures, characterized by an expansive search space, rendered the discovery and optimization of intricate exposure patterns a daunting challenge. Initial attempts with a steepest descent (SD) method proved inadequate, thwarted by the labyrinthine topology of the search space and the myriad of variables at play. The hybrid approach, which synergized global search capabilities afforded by genetic algorithms (GAs) with localized optimization via the steepest descent (SD) methodology, yielded marginal improvements in the quality of GA-optimized structures. The optimization process hinged upon the formulation of a fitness function while concurrently reducing tolerances. A comprehensive analysis of mutation, reinsertion, crossover, and selection operators further enriched the optimization process. The

GA emerged as a dependable tool, accurately predicting scanning patterns for the 100-nm T-gate and asymmetric recess gate designs. This simulation and optimization tool stands poised to expedite EBL response times by circumventing the protracted trial-and-error phase.

A compelling alternative for achieving sub-22 nm resolution resides in the realm of electronic beam lithography (EBL) [5]. EBL surpasses the limitations imposed by conventional optical lithography methods, directly imprinting intricate circuit designs onto silicon. The principal challenge manifests in the restricted rate of data transfer, necessitating judicious handling. The process entails the projection of each rectangle through a single electrical shot, facilitated by a variable shaped beam in a standard electron beam lithography (EBL) system. A gentle approach is deemed suitable for this endeavor. A pioneering technique, characterized as the character projection (CP) method, extends the purview of electron beam lithography (EBL). CP method relies on the deployment of a stencil to simultaneously project multiple intricate designs. However, the number of characters that can be accommodated is constrained by spatial limitations. Notably, VSB must inscribe unspecified patterns. A critical challenge surfaces in the task of systematically incorporating characters onto the CP stencil to optimize operational efficiency. The study critically examines the factors at play during the production of electronic beam lithography stencils, offering a novel system that enhances character selection and stencil placement. The researchers introduce a 2-D simulated annealing framework, coupled with a look-ahead sequence pair assessment technique, complemented by an iterative Hamilton-path based 1-D stencil creation procedure. These innovations collectively culminate in a 50% reduction in projection time when juxtaposed with conventional stencil designs housing non-overlapping characters.

The domain of complex hybrid lithography, colloquially known as MP EBL, represents a transformative technique that amalgamates multiple patterning methodologies with e-beam lithography [6]. The ramifications of this approach become pronounced as the number of features diminishes, and circuit complexities amplify. Within this context, the notion of "minimal vertex deletion K-partition issue" emerges as a pivotal challenge, entailing the decomposition of a hybrid lithography architecture through the prism of a specific partitioning technique. The intricate graph construction process necessitates the introduction of virtual vertices positioned between two feature vertices for each stitch candidate. Researchers introduce a primal-dual methodology as the linchpin for computing the smallest odd-cycle cover, for a predetermined value of K, equal to 2. Chain decomposition emerges as a potent strategy for eliminating edges that cannot conduce to the formation of a cycle. For values of K exceeding 2, the primal-dual solver offers a localized search strategy buttressed by random initialization. These pioneering methodologies usher in a substantial reduction in EBL consumption, amounting to 64.4% with double patterning and 38.7% with triple patterning, when juxtaposed with a conventional two-stage procedure.

The work expounded in [7] offers a comprehensive inquiry into the exposure parameters governing electron beam lithography, employing the AR7520 negative tone electron beam resist (NTEB). Notably, scientists sought to diminish the dimensions of the resist, a pursuit that necessitated the augmentation of beam voltage, resist thickness, and aperture diameter. Augmented beam energies and thicker resist layers correlate with reduced energy deposition within the resist layer, consequently mandating higher doses for attaining specific dot sizes. This empirical finding finds substantiation in electron scattering Monte Carlo models. The range of forward scattered electrons, contingent upon dot size and exposure conditions, spanned from 50 to 170 nm. A meticulous analysis revealed a systematic association between larger dimensions and reduced doses, thereby constricting the backscattering electron range to a mere 560 nm. The construction of nanometric devices was facilitated through the judicious implementation of a straightforward lift-off method, entailing the augmentation of exposure settings and controlled baking to enhance the etch resistance of the resist.

The research presented in [8] introduces a tool underpinned by genetic algorithms (GA) for the simulation and optimization of electron-beam lithography. The focal point of the fitness function hinges on the inverse Euclidean distance to the target, culminating in the determination of a resampled resist profile. This research undertakes a systematic exploration of the boundaries and limitations inherent to the fitness function. It becomes evident that the fracas function, while serving as a valuable tool, possesses limited applicability, especially in instances characterized by minor irregularities in the profile or an abundance of resampled chain nodes, which may engender synchronization challenges. The judicious recourse to a distinct fitness function, derived from the confines of the restricted resist profile region, is advocated. Both in principle and experimental scenarios, this refined fitness function systematically eradicates minor imperfections from the ideal resistance profile, thereby exerting a salutary influence on the overall quality of the structure.

The adoption of character projection within e-beam lithography engenders a substantial uptick in throughput [9]. The efficacy of this process hinges on the meticulous design and refinement of stencils. Kuang and Young introduce a 2-D Bin-Packing Stencil Optimization (BPSO) heuristic, a concept underpinned by merit frequency/area (f/A) for accurately ascertaining potential characters and assessing the occupied area of each character before placement. The optimization process compels researchers to meticulously ponder character incorporation onto the CP stencil, with a keen eye towards operational streamlining. The research scrutinizes the facets concomitant with the production of electronic beam lithography stencils, unveiling a novel system that not only optimizes character selection but also refines stencil placement. The researchers introduce a 2-D simulated annealing framework, complemented by a look-ahead sequence pair assessment technique, all while proposing an iterative Hamilton-path based 1-D stencil creation procedure. These innovations translate into a 50% reduction in projection time when compared to conventional stencil designs featuring non-overlapping characters.

The scholarly discourse presented in [10] embarks on an exploration of X-ray lithography techniques, with the overarching objective of augmenting the absorbed energy density of the resist. The purview of this review encompasses an array of pivotal subjects, encompassing electron-beam energy, wavelength, X-ray quantum efficiency, and the utilization of the X-ray window. The optimal radiation source for Si or polymer mask membranes, characterized by a diminutive B-window and the absence of an X-ray window, resides in K-line radiation emitted by Al or Si sources. L-line sources emerge as highly beneficial for extensive Beryllium windows. The laboratories employ photolithography and electron-beam lithography techniques for the fabrication of polymer film X-ray masks, fostering a comprehensive exploration of the advantages and drawbacks inherent to these masks. Notably, polymer film masks assume a pivotal role in replicating etched SiO2 patterns with remarkable precision.

The empirical findings suggest that hybrid lithography, an amalgamation of multiple patterning and electron beam lithography (EBL), harbors the potential to enhance pattern resolution concomitant with the burgeoning intricacy of circuits and the diminishing dimensions of features. The term "minimal vertex deletion K-partition issue" conveys the intricacy of dissecting a hybrid lithography layout through a methodological prism, wherein the endeavor revolves around the minimization of vertex removals. During the intricate process of constructing the conflict graph, an ephemeral vertex is judiciously interposed amidst two feature vertices for each prospective stitch candidate. The researchers proffer a pragmatic and meticulously orchestrated primal-dual (PD) methodology to elucidate the quandary of identifying the smallest odd-cycle cover, contingent upon the stipulation that K=2. Chain decomposition emerges as the modus operandi employed for the eradication of edges that languish bereft of cycle instantiation. Additionally, the scientists delve into the intricacies of two PD methodologies, one entailing planarization and the other opting for its absence. Furthermore, a novel technique, denominated as random initialized local search, underpins the underpinning principles, predicated on the recurrent application of PD. The fruits of these endeavors culminate in a substantial reduction, quantified at 65.5 percent for double patterning and 38.7 percent for triple patterning, in EBL consumption vis-a-vis a two-stage procedure.

The traction gained by the fabrication of 1D gridded patterns is surging in response to the inherent constraints that plague optical lithography, particularly the limitations in resolution [12]. The widely-adopted technique of Self-Aligned Double Patterning (SADP) assumes a pivotal role in one-dimensional printing. However, as feature dimensions encroach upon the 20-nanometer threshold and beyond, the inadequacies of SADP become apparent, particularly when catering to one-dimensional configurations necessitating the deployment of a solitary trim mask. Notably, the amalgamation of SADP with electron-beam lithography (e-beam lithography or EBL) has become a focal point of investigation. This scholarly inquiry is fundamentally centered on the enhancement of efficiency within the realm of 1D pattern printing, predicated on the judicious curtailment of e-beam shots while adhering to predefined constraints on line end extension. Two distinct paradigms, each furnishing a blueprint for the realization of a plan via the confluence of e-beam lithography and a trim mask, are contemplated. The first methodology hinges on e-beam end cutting in tandem with a trim mask, while the second method relies on the symbiosis between an electron beam and a trimming mask to eliminate superfluous components. The development and refinement of both approaches are orchestrated through the prism of Integer Linear Programming (ILP). Plausible experimental solutions are advanced for both formulations of Integer Linear Programming (ILP), thereby setting the stage for a comparative analysis of these strategies employed in the creation of 1D layouts.

The efficacy of electron beam lithography, or EBL, is known to dwindle as the manufacturing scale dwindles beyond the 10-nanometer threshold. Character projection (CP), an endeavor geared towards amplifying throughput, might harness the benefits stemming from the circumvention of character overlap, as postulated in a recommendation [13]. The endeavor to craft a high-level 2D stencil is fraught with computational intricacies. Remarkably, no polynomial-time optimal solution has been forthcoming for the pivotal stage of 1D row ordering.

It's noteworthy that the row ordering quandary, constituting a pivotal component of stencil planning, finds itself ensconced within the realms of polynomial time optimal solutions that captivate the attention of diligent researchers. Empirical endeavors, coupled with pertinent data, attest to the veracity and efficacy of the aforementioned technique.

The adoption of low-energy electron beam lithography holds substantial promise as a next-generation lithographic technique, particularly for applications embracing the 21-nanometer half-pitch node and beyond [14]. The rationale behind this preference lies in its propensity to induce less substrate damage, exhibit heightened sensitivity to resist, and attenuate the deleterious effects of proximity. To facilitate high-throughput manufacturing, there is a pressing need for the development of more capacious electron beams, grids, and dosages within the framework of low-energy electron beam lithography systems, or LEBL LGD. An inherent manifestation of this technique is the electron shot noise, which, in turn, engenders an escalation in edge roughness and dimensional deviation, exerting a pronounced influence on patterning precision. The overarching strategy espoused by this research effort aligns seamlessly with the parameters set forth by the International Technology Roadmap for Semiconductors. This alignment is realized through a judicious blend of throughput optimization and the preservation of unwavering precision in pattern accuracy, an accomplishment predicated on innovative technological underpinnings. The system is underpinned by a pioneering method tailored to pattern prediction, thereby facilitating an accurate quantification of variability emanating from shot noise. Furthermore, it employs a mathematical optimization procedure to discern the optimal writing settings. The novel approach to pattern prediction strikes a delicate balance between precision and computational resources. Empirical evidence underscores the efficacy of this pioneering technology, particularly through its application in a static random-access memory circuit. Rigorous evaluations pertaining to electrical performance are conducted, encompassing gate-slicing and open transistor models, culminating in quantitative data that hints at a potentially substantial amplification in the level of static noise margin.

The malaise of long-range fogging endemic to contemporary electron-beam lithography (EBL) bestows a burdensome array of challenges, including superfluous exposure and the engenderment of plan abnormalities. This article proffers a methodical approach to combat this persistent fogging menace. The overarching objective is the minimization of fogging variability throughout the installation process, predominantly through the judicious employment of standard cells. This endeavor is complemented by a parallel undertaking that involves the uniform reduction of dosage across the entirety of the microchip. The foundation for this endeavor rests upon an efficient, albeit not entirely precise, fogging effect model. In consonance with the research delineated in [15], the researchers harness the power of fast Gauss Transforms and Hermite expansion (GTH) to craft an intricate hazy source model, in conjunction with a precise and efficient evaluation methodology. This strategy, underpinned by an iterative assessment, serves to ameliorate variations within the ambit of global placement. Furthermore, it achieves a remarkable 30.2-fold acceleration in the computation of convolutions, all while maintaining an absolute average error quotient of a mere 2.35 percent. The implementation of fogging-aware regulations and strategic placement strategies serves to elevate the quality of placement, while simultaneously minimizing fluctuations in fog levels. This methodological approach strikes an intricate balance, allowing for the preservation of optimal runtime performance and wirelength accuracy, all while effecting a notable reduction in fogging variability to the tune of 35.4 percent levels.

The research in [16] offers a novel, memory-efficient approach to the construction of scanning-beam lithography methodologies. The crux of the methodology revolves around the quest to identify an exposure pattern that minimizes the dissonance between the intended and actualized output image. The enormity of this challenge becomes apparent when one considers the astronomical number of pixels, ranging in the millions to billions, that correspond to the multitude of free variables and sets within this intricate problem domain. The proposed approach introduces a prudent segmentation of the problem domain into overlapping subdomains, each replete with distinct border constraints. The solution to each subdomain is meticulously sought through the auspices of a restricted gradient search technique, precisely the L-BFGS-B algorithm. Leveraging the nimbleness of the fast Fourier transform and harnessing the innate sparsity of the problem, the computation time is effectively truncated. This novel approach, in contrast to antecedent methodologies that sought to curtail memory usage through the inclusion of additional subdomains, which, in turn, necessitated heightened computational exertions, yields a remarkable outcome. The suggested approach engenders a 67 percent reduction in memory utilization, all while registering a 27 percent augmentation in processing time, as exemplified in the scenario involving 30 million variables. The potential applications span the gamut from focused ion beam deposition to scanning electron beam lithography and scanning laser lithography, predicated on judicious alterations to the extant methodology.

The research documented in [17] harnesses the ZBA23 (Raith) electron beam lithography equipment to probe the intricacies of electron resist AR-N 7520 profiles at varying exposure doses and preordained exposure patterns. The empirical panorama offers a plethora of geometric quality criteria for resist profile cross-sections. An empirical modeling framework is brought to bear in order to unearth the intricate interplay between resist profile configuration and exposure dose. These quality metrics, subject to a multicriteria optimization regimen, serve as the touchstone for articulating the technical requisites of freshly minted profiles.

Electron-beam lithography (EBL) is an indispensable technique employed to achieve the fabrication of nanopatterns at exceptionally high resolutions [19]. In the realm of electron beam lithography, the presence of the near proximity effect exerts a discernible influence on the quality of the resulting patterns, consequently impacting the performance of various applications. When confronted with the challenge of crafting large-scale and intricately structured designs, traditional methodologies for mitigating the proximity effect, such as the removal of cells or pathways during growth simulation, necessitate substantial computational resources. The erudite authors propose an innovative approach termed "short-range Proximity Effect Correction (PEC)," a method that strategically allocates essential development time to convert pattern feasibility into the shortest route problem. By seamlessly integrating this evaluation method with the insights derived from swarm intelligence, the authors orchestrate a significant enhancement in the dispersion of the electron dose within the domain of EBL. This intricate technical maneuver culminates in the generation of the U-shaped split-ring resonator configuration, emblematic of the prowess intrinsic to the PEC technique. Furthermore, it results in the creation of an exposure pattern that impeccably adheres to the desired outcomes. In the pursuit of crafting intricate designs that meticulously adhere to constraints and minimize processing costs, the PEC methodology emerges as an unparalleled exemplar of technical finesse.

The meticulous research documented in [20] embarks on a comprehensive examination of the processing intricacies, microstructural characteristics, and mechanical properties inherent to the realm of Ti-6Al-4V Electron-Beam Powder Bed Fusion (E-PBF) additive manufacturing. The discerning researchers cast their astute gaze upon aspects such as substrate consolidation, repair, and integration, meticulously scrutinizing the bonding behavior and microstructural nuances within the hallowed confines of the bonding region. It is discerningly postulated that plastic stresses engendered within the Ti–6Al–4V substrate primarily assume responsibility for mechanical imperfections and subsequent failures. An intriguing facet that comes to the forefront in this scholarly exploration is the concept of hybridization, an amalgamation that reverberates through the formation of E-PBF and the bonding of substrates. This concerted research endeavor not only advances the corpus of essential knowledge but also endows the hybrid E-PBF additive manufacturing technique with augmented efficacy.

The research elucidated in [21] delves into the selectivity associated with reactive ion etching of functional materials in the intricate tapestry of nano electronic device topologies. Within this intricate tableau, characterized by the creation of nanostructures measuring smaller than 50 nanometers, a multitude of materials undergoes meticulous scrutiny. These materials encompass monocrystalline silicon, low-k organo-silicate glass (OSG) on silicon substrates, metallic Ta layers, dielectric SiO2 layers, Al2O3, HfO2, and Si3N4. Notably, the diminutive HSQ resist masks, scarcely measuring a mere 10 nanometers, emerge as the vanguard of innovation, capable not only of nurturing prototypes of micro- and nano-electronic devices but also of engendering structures characterized by towering aspect ratios and layer thicknesses that flirt with the tens of nanometer range. The ramifications of this pioneering technique extend their embrace to the creation of structures replete with high aspect ratios, all while adhering to the humble realm of tens of nanometers.

As photolithography faces inherent limitations in achieving shrinking feature sizes, alternative patterning techniques have garnered increasing attention, driven by the relentless descent in feature dimensions [22]. The advent of next-generation lithography (NGL) promises the precise and efficient fabrication of a myriad of products. This erudite article scrutinizes the challenges entailed by the ascent of NGL and offers prescient insights into potential solutions. Within the pantheon of solutions, Extreme Ultraviolet Lithography (EUVL) emerges as the undisputed choice for manufacturing designs smaller than the 10-nanometer threshold, aligning adeptly with market demands. As EUVL technology undergoes rigorous development, it prepares to assume its rightful place in the market. The mantle of maskless lithography finds resonance not only in research and development but also in the domains of mask and mold manufacturing, as well as the niche arena of low-volume chip design. While guided self-assembly has made promising strides in laboratory settings, the path to refining next-generation lithography (NGL) remains fraught with challenges yet to be overcome. Amidst this myriad of choices, nanoimprint lithography emerges as the preeminent champion in the realm of nanofabrication, distinguished by its inherent simplicity, cost-effectiveness, and the ability to yield resolutions of unparalleled finesse, all while maintaining impressive throughput. However, the journey to establish the reliability and validity of these endeavors is replete with the exigencies of technological advancement and an array of formidable challenges. Ultimately, this compendium serves as a testament to the myriad of techniques, each offering its unique value proposition, and underscores the salient distinctions that set them apart.

The hallowed precincts of scientific exploration, as articulated in the publication by [23], bear witness to the advent of a novel in situ imaging methodology and an accompanying detector array that seamlessly integrates with the focused electron beam. The structural compactness of this electron beam detector array, boasting an impressive tally of 2 trillion pixels, is harmoniously consonant with the contours of FinFET CMOS logic. This technological marvel is distinguished by a wide dynamic range, rapid response times, and an enhanced responsivity. The incorporation of this detector array is two-fold in nature, as it finds domicile within the confines of the tool itself while also adorning the wafer. Furthermore, the intrinsic capacity of the sensing/storage node to store the e-beam imaging pattern and detection data sans the exigency of external power engenders the feasibility of offline electrical reading. This virtuoso of technology endows the scientific fraternity with the ability to furnish expeditious feedback pertaining to the dosage, accelerating energy, and intensity distributions enshrouding the e-key beam upon the canvas of projected wafers.

The magnanimous potential inherent in electron beam lithography (EBL) crystallizes in the ability to attain manufacturing resolutions that transcend the confines of manometer dimensions [24]. Alas, the prevailing incarnations of EBL remain handicapped in their endeavor to engender ordered 3D nanoforms. The clarion call for resolutions that straddle the realms of functionality and structural integrity is vociferously answered by the trailblazing researchers, who, armed with a voltage-regulated 3D EBL, usher forth the dawn of a new era. With judicious precision, these pioneers orchestrate the successful fabrication of operational 3D nanostructures, boasting resolutions that stoop to the level of a mere 15 nanometers. It is worth noting that the hallowed environs of an all-aqueous milieu served as the crucible for these technological triumphs, ensuring unparalleled precision and authenticity in the resultant creations. The utility of Recombinant Spider Silk Proteins (RSSP) emerges as a formidable asset in the realm of developing robust and intricate nanoscale 3D printers. The deployment of polymorphic spider silk proteins within the hallowed matrix of a three-dimensional protein framework endows them with the capacity to interact with energetic electrons at varying depths, thereby yielding to structural transformations that operate at the molecular stratum. This unique quality facilitates the manipulation of these spider silk proteins, effecting changes that transcend the boundaries of mere physicality. The resultant three-dimensional nanostructures are endowed with the capability to harbor physiochemical and/or biological functionalities, either through genetic or mesoscopic manipulation of the spider silk proteins. This groundbreaking technique bespeaks the ability to synthesize 3D nanodevices and nanocomponents that are hierarchically structured and functionally imbued. The manifold applications that arise in the wake of this innovation span an eclectic gamut, encompassing the realms of biomimetics, medical devices, and nanoscale robots, each poised to harness the potential of these technological marvels.

The lithographic nano-structuring method under consideration derives its efficacy from the interaction volume of the minuscule electron beam, juxtaposed with the selective ion exposure spanning the tens of nanometers-long domain of the polymer resist [25]. The profound research inquiry elucidates that the lion's share of the beam's energy metamorphoses into resistance, setting the stage for an enthralling interplay of forces that culminate in the attainment of sub-10 nanometer precision. This monumental achievement is buttressed by remarkable energy efficiency and an ephemeral proximity impact, catalyzing the emergence of non-uniform resistance and depth-dependent dissolving rates. In the maelstrom of these dynamics, the conventional yardstick for measuring resist contrast is rendered obsolete. This erudite treatise introduces a novel paradigm in the computation of resist contrast, a paradigm that is born of ingenuity and expounded with sagacity. Under the aegis of a 30 keV Ga+ ion beam, the hallowed contrast and ion energy values for PMMA resist stand recorded at 3.1 and 42 nm, respectively, paving the way for a renaissance in the domain of lithographic precision.

The inexorable surge of interest in magnetic skyrmions, characterized by their unique topological spin textures, has propelled them to the forefront of scientific exploration [26]. These enigmatic structures bear the potential to metamorphose the landscape of magnetic memory devices, whilst simultaneously ushering in a pantheon of intriguing physical phenomena that encompass chiral magnon and skyrmion glass states. The sine qua non for harnessing the transformative potential of magnetic skyrmions lies in the ability to control and fabricate them on a grand scale, a challenge that has vexed scientific minds. The echelons of innovation reverberate with the clarion call for a novel technique, one that eschews the need for external magnetic fields. In this paradigm-shifting approach, christened as "skyrmion lithography," a graphic pattern generator and a focused electron beam join hands to "print" skyrmions in any desired configuration, be it whimsical or pragmatic. This revolutionary breakthrough unfetters the shackles of convention, endowing researchers with the power to conjure arbitrary skyrmion patterns, thereby broadening the horizons of topological magnetism and opening doors to uncharted realms of scientific exploration.

The burgeoning research inquiry in [27] casts its spotlight upon zinc oxide (ZnO), an erstwhile unassuming material that now stands poised on the cusp of transformational applications in the expansive landscape of large-area electronics. A tantalizing promise of low-cost production through the vehicle of solution-processing technologies beckons, yet the milieu of high-resolution manufacturing processes for ZnO languishes in the doldrums of limited exploration. This scholarly opus ushers forth a novel technique, christened as "DW-EBL," a nomenclature that abbreviates the nomenclature for "Directed Writing Electron Beam Lithography." DW-EBL deftly harnesses solution precursors, casting them in the role of negative tone resists, all in pursuit of engendering the coveted micron/nano-FETs (Field-Effect Transistors). The discerning eye of scientific scrutiny discerns that the width of the precursor pattern exerts a profound influence upon the mobility and current density of ZnO FETs, culminating in enhancements that scale up to two orders of magnitude within the precincts of the nanoscale realm. Furthermore, the research delves into the morphological evolution of ZnO grains, a transformation wrought by the subtle nuances of nanoscale precursor patterning. This exploration portends not only a deeper comprehension of ZnO's behavior but also the tantalizing prospect of large-scale integration of solution-processed nanoscale oxide FETs.

The burgeoning realm of quantum technology resonates with the allure of semiconductor quantum dots, self-organizing entities that hold the promise of serving as two-level systems, poised to catalyze a renaissance in the annals of photonic quantum technology [28]. These quantum dots emerge as nearly pristine founts of quantum light, rendering them supremely adept at facilitating the intricate dance of spin-photon interactions. The resplendent pages of this study unveil a quantum dot-based device, a device that boasts the seamless integration of a circular Bragg grating. This audacious undertaking attains a veritable tour de force, characterized by a photon extraction efficiency that swells to a staggering 244 percent. The implications of this feat reverberate across the expanse of quantum networks and photonics applications, opening up tantalizing vistas of progress and innovation.

The radiant star of plasmonics ascends to greater heights, propelled by the inexorable march of advancements in micro- and nanofabrication [29]. The alchemy of combining electron-beam lithography with gold ion-beam lithography begets a potent amalgamation, one that bequeaths unto the scientific fraternity the power to engender complex plasmonic nanostructures, both in two and three dimensions. These meticulously aligned structures, bedecked with superior optical properties and functionalities, emerge as veritable champions in the arenas of plasmonics, nanooptics, meta-surfaces, plasmonic sensing, and an eclectic array of allied applications.

The arena of focused ionizing radiation beams, whilst heralded for their unparalleled spatial precision, grapples with the impracticality of scaling up for large microstructure arrays [30]. This astute research posits a revolutionary proposition, advocating for a recalibration of x-ray lithography settings, one that bestows the ability to fashion sub-micropores within the embrace of low-sensitivity polyethylene terephthalate. This optimization metamorphoses into the creation of micropores, their diameters expanding to reach a remarkable 0.4 micrometers, all spanning a vast substrate expanse, whilst simultaneously maintaining a towering aspect ratio sets.

This research postulates the modification of x-ray lithography settings to effectuate the creation of sub-micropores within low-sensitivity polyethylene terephthalate. This optimization endeavor yields the fruition of micropores, characterized by diameters extending to a formidable 0.4 micrometers, sprawling across a substantial expanse of substrate, all while sporting an impressive high aspect ratio.

The realm of high-resolution circuit patterning attains its zenith through the auspices of electron beam lithography (e-beam lithography) [31]. However, the intricacies of electron scattering, manifesting within both the resist and substrate, engender constraints upon the hallowed lithographic resolution. To redress this formidable challenge, researchers have adroitly harnessed the prowess of mathematical modeling and correction methodologies. These methodologies proffer circuit layouts of unparalleled precision but are not bereft of computational costs, their execution facilitated by the modern arbiters known as GPGPUs (General-Purpose Graphics Processing Units).

Electron-beam lithography (EBL) emerges as a formidable technological bastion, endowed with the virtuosity to conjure structures on the nanoscale, yet its ascent is marred by the specter of dose inadequacy when navigating through the labyrinthine terrain of thick resist layers [32]. In a spirited response to this conundrum, the visionary researchers have bequeathed the world with an ingenious stratagem christened "proximity effect correction (PEC)," a stratagem that serves as the lodestar guiding the creation of superlative nanostructures through expeditious and cost-effective exposures.

The traditional guise worn by EBL is that of a "blind" technique, bereft of the invaluable resource that is real-time feedback concerning the pattern etched by the electron beam [33]. The epochal arrival of self-developing nitrocellulose resist (SNR) heralds a paradigm shift, bestowing upon the scientific fraternity the boon of real-time feedback and the wherewithal to optimize the electron beam's parameters with alacrity. This trailblazing approach emboldens researchers to attain higher resolutions, all while illuminating a larger canvas compared to the constraints inherent in conventional methodologies.

The repository of erudition unearthed in [34] delves into the heart of the matter through the prism of process simulation and the intricate arsenal of mathematical modeling tools. These tools, wielded with a surgeon's precision, serve as the crucible within which the performance of PMMA resist is evaluated, and EBL nano-patterning resolution undergoes a transformative metamorphosis. An assortment of parameters, ranging from the energy deposition function to the proximity effect parameters, stands subjected to meticulous scrutiny within this cerebral tapestry.

The scholarly expedition chronicled in [35] embarks upon a foray into the realm of the single-step direct-write nanolithography, christened as Focused Electron Beam Induced Deposition (FEBID). This avant-garde technique leverages a manometer-sized electron beam to effectuate the disintegration of precursor gas molecules, unearthing a veritable treasure trove of possibilities in the fertile domain of nanofabrication sets.

Hunan University (HNU) casts its mantle of innovation in the form of HNU-EBL, a three-module paradigm that unfolds with the grace of a finely choreographed ballet [36]. Within this intricate ballet, the movements encompass Monte Carlo simulation, point spread function fitting, and the meticulous assessment of edge placement inaccuracy. HNU-EBL emerges as the harbinger of sub-10 nanometer EBL simulations, endowed with the power to elevate the fabrication of nanoscale devices to an unparalleled zenith levels.

Electron beam lithography (EBL), although imbued with tremendous potential in the hallowed domain of photomask production, grapples with the formidable specter of CD distortion, a phenomenon inextricably linked to heating [37]. As a sagacious solution to this conundrum, the concept of subfield scheduling takes center stage, seeking to mitigate heating-induced CD distortion. This groundbreaking study unfurls a novel approach to surmounting the constrained m–nTSP problem, sculpting an optimized subfield scheduling paradigm tailored for the intricate realm of e-beam photomask manufacturing.

The inexorable specter of resist heating casts a long shadow over the hallowed precincts of high-voltage, high-throughput electron beam mask writing [38]. The erudite researchers advance a proposition that aims to temper the tempestuous CD distortion arising from resist heating through the meticulous optimization of subfield writing sequences. In this audacious endeavor, the coveted fruits of improved semiconductor industry productivity beckon as the ultimate reward.

CD distortion, the elusive specter born of resist heating, lingers as a constant concern in the domain of high-throughput e-beam mask writing [40]. The enterprising researchers proffer a resolute suggestion, one that revolves around the augmentation of the e-beam current density and the judicious refinement of the mask writing sequence, all under the imprimatur of improved subfield scheduling. Simulations, the veritable crucible of scientific inquiry, cast a benevolent light upon this stratagem, indicating that it holds the power to ameliorate resist temperature sans any compromise on mask writing productivity. The vistas of improved CD control beckon alluringly on the horizon, ushering forth the promise of progress. As researchers traverse this intellectual odyssey, the parameters governing the performance of these various models come under scrutiny, and the intricate tapestry of their distinctions is rendered manifest, facilitating the discernment of the most fitting approach for their specific applications.

3. Pragmatic Analysis

It was discovered that there is a significant degree of diversity among the various EBL Optimization Models currently in use when a thorough analysis of these models was conducted. Thus, this section compares various aspects of each of those models to help readers determine which EBL models are best. These comprise their computational complexity (CC), scalability (S), deployment cost (DC), computational delay (D), and processing accuracy (A). Based on their internal module deployment characteristics, these parameters were quantized into four categories: Low Value Range (LVR=1), Medium Value Range (MVR=2), High Value Range (HVR=3), and Very High Value Range (VHVR=4). Table 1 presents the comparison according to this evaluation strategy as follows,

Table 1. Performance evaluation of different EBL Optimization models

EBL Model	**A**	**CC**	**D**	**DC**	**S**
PMMA [1]	MVR	MVR	HVR	HVR	LVR
PE [2]	MVR	HVR	HVR	MVR	MVR

HLith [3]	LVR	HVR	HVR	VHVR	LVR
GSD [4]	HVR	MVR	HVR	HVR	MVR
VSB [5]	HVR	MVR	VHVR	VHVR	MVR
MP EBL [6]	HVR	HVR	HVR	MVR	HVR
NTEB [7]	HVR	MVR	MVR	HVR	MVR
GA [8]	VHVR	LVR	LVR	LVR	VHVR
BPSO [9]	VHVR	LVR	LVR	MVR	VHVR
Xray BW [10]	MVR	MVR	MVR	MVR	HVR
PD [11]	MVR	MVR	MVR	HVR	MVR
SADP [12]	LVR	HVR	HVR	VHVR	MVR
CP [13]	HVR	MVR	HVR	MVR	HVR
LEBL LGD [14]	HVR	HVR	MVR	MVR	LVR
GTH [15]	HVR	HVR	MVR	HVR	HVR
LBFGSB [16]	MVR	VHVR	MVR	MVR	HVR
ZBA23 [17]	HVR	HVR	LVR	LVR	MVR
FFT [18]	HVR	HVR	MVR	MVR	HVR
PEC [19]	MVR	MVR	MVR	HVR	MVR
E-PBF [20]	MVR	MVR	HVR	MVR	MVR
EUVL [22]	HVR	HVR	HVR	MVR	LVR
RSSP [24]	HVR	MVR	LVR	HVR	HVR
DW-EBL [27]	HVR	MVR	MVR	MVR	HVR
QDM [28]	MVR	HVR	MVR	MVR	HVR
Xray EBL [30]	MVR	MVR	HVR	HVR	HVR
PEC [31]	HVR	MVR	HVR	HVR	HVR
SNR [33]	MVR	LVR	MVR	HVR	MVR
PMMA [34]	HVR	MVR	HVR	HVR	MVR
FEBID [35]	HVR	HVR	HVR	MVR	HVR
FFT [36]	HVR	MVR	MVR	LVR	VHVR
MN TSP [37]	VHVR	LVR	LVR	MVR	VHVR
MSTSP [38]	VHVR	LVR	MVR	LVR	VHVR

This assessment reveals that certain algorithms, namely GA [8], BPSO [9], MN TSP [37], and MSTSP [38], exhibit higher accuracy, rendering them suitable for demanding EBL applications. Additionally, Table 1 demonstrates that the following algorithms possess lower complexity and are well-suited for EBL applications where computing resources are limited: GA [8], BPSO [9], SNR [33], MN TSP [37], and MSTSP [38]. Similarly, Table 1 highlights that GA [8], BPSO [9], ZBA23 [17], RSSP [24], and MN TSP [37] demonstrate reduced latency, making them appropriate for high-speed EBL applications. Moreover, Table 1 indicates that GA [8], ZBA23 [17], FFT [36], and MSTSP [38] incur lower deployment costs, making them applicable to cost-effective EBL applications. Lastly, Table 1 underscores that algorithms with greater scalability resources, including GA [8], BPSO [9], FFT [36], MN TSP [37], and MSTSP [38], can be deployed effectively in highly scalable EBL applications. Equation 1 can be used to evaluate the new EBL Optimization Metric (EBLOM), which was created by combining these metrics,

$$EBLOM = \frac{A}{4} + \frac{1}{CC} + \frac{1}{D} + \frac{1}{DC} + \frac{S}{4} \dots (1)$$

This evaluation reveals that the following have better EBL performance: GA [8], BPSO [9], MN TSP [37], MSTSP [38], FFT [36], RSSP [24], ZBA23 [17], DW-EBL [27], CP [13], and FFT [18]. As a result, they can be used for high scalability, low cost, low complexity, and high accuracy data EBL application scenarios. Researchers can determine the best models for their performance- and application-specific EBL applications based on the results of this evaluation process.

4. Conclusion

This text initially delves into a comprehensive examination of various EBL optimization models, scrutinizing them with respect to their specific deployment nuances, contextual advantages, application-specific constraints, and potential for future functionalities. This exploration leads to the observation that bioinspired models outperform other approaches in terms of operational efficiency, thus warranting their application across a diverse range of EBL optimization scenarios. A comparative analysis of these models' internal performance attributes reveals that GA, BPSO, MN TSP, and MSTSP exhibit higher levels of accuracy. However, it is noteworthy that GA, BPSO, SNR, MN TSP, and MSTSP, owing to their lower complexity, are amenable to deployment in EBL applications demanding precision even when computing resources are constrained.

Moreover, the evaluation demonstrates that GA, BPSO, ZBA, RSSP, and MN TSP exhibit reduced latency, while GA, ZBA, FFT, and MSTSP also offer cost-effective deployment options, making them suitable for both low-cost and high-speed EBL applications. Similarly, GA, BPSO, FFT, MN TSP, and MSTSP are identified as appropriate choices for highly scalable EBL applications due to their remarkable scalability capabilities.

The amalgamation of these diverse metrics into an EBL Optimization Metric reveals that GA, BPSO, MN TSP, MSTSP, FFT, RSSP, ZBA, DW-EBL, CP, and FFT display superior overall performance, positioning them as viable options for EBL applications characterized by high scalability, low latency, low complexity, low cost, and high accuracy requirements. Researchers can leverage these findings to tailor models that best suit their specific EBL performance and application needs.

Furthermore, researchers have the potential to enhance these models' performance in the future by combining various bioinspired methodologies and applying them to a wide array of objective problems. The integration of Convolutional Neural Networks (CNNs) and other deep learning and machine learning models into the EBL optimization landscape holds promise for further improving EBL characteristics, ultimately resulting in enhanced preemptive performance optimization across various application scenarios.

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