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Empirical Analysis of Electron Beam Lithography Optimization Models from a Pragmatic Perspective

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Abstract: Electron Beam (EB) lithography is a process of focussing electron beams on silicon wafers to design different integrated circuits (ICs). It uses an electron gun, a blanking electrode, multiple electron lenses, a deflection electrode, and control circuits for each of these components. But the lithography process causes critical dimension overshoots, which reduces quality of the underlying ICs. This is caused due to increase in beam currents, frequent electron flashes, and reducing re-exposure of chip areas. Thus, to overcome these issues, researchers have proposed a wide variety of optimization models, each of which vary in terms of their qualitative & quantitative performance. These models also vary in terms of their internal operating characteristics, which causes ambiguity in identification of optimum models for application-specific use cases. To reduce this ambiguity, a discussion about application-specific nuances, functional advantages, deployment-specific limitations, and contextual future research scopes is discussed in this text. Based on this discussion, it was observed that bioinspired models outperform linear modelling techniques, which makes them highly useful for real-time deployments. These models aim at stochastically evaluation of optimum electron beam configurations, which improves wafer's quality & speed of imprinting when compared with other models. To further facilitate selection of these models, this text compares them in terms of their accuracy, throughput, critical dimensions, deployment cost & computational complexity metrics. Based on this discussion, researchers will be able to identify optimum models for their performance-specific use cases. This text also proposes evaluation of a novel EB Lithography Optimization Metric (EBLOM), which combines multiple performance parameters for estimation of true model performance under real-time scenarios. Based on this metric, researchers will be able to identify models that can perform optimally with higher performance under performance-specific constraints.

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

1. Introduction

Design of an efficient Electron Beam (EB) Lithography model is a multidomain process, that involves beam blinking control, beam deflection control, stage control, laser inference system, control of motors, electron lens control, and other deployment-specific models. Modelling so many interfaces require design & integration of various Machine Learning Models (MLMs), that can be integrated on the EB test bed for efficiently operating different components. A typical EB Lithography Model [1] is depicted in figure 1, wherein different components along with their interconnections can be observed. Blocks that control beam blinking & deflection interfaces are modelled via a high-speed data processing method, that is controlled by a bioinspired or linear processing model. These models also generate control signals for staging devices, which assists in modifying movements of different motors & laser inference blocks. Due to such high-speed operations, these models might increase critical dimensions, which causes reduction in wafer quality. To improve this quality, researchers have proposed different techniques that can optimize beam currents, improve periodicity between electron flashes, and optimize re-exposure of regions

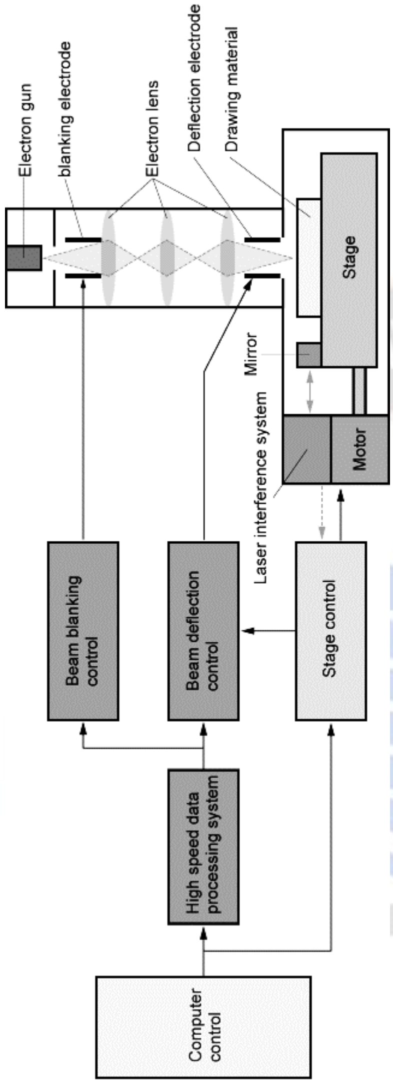

Figure 1. Design of a Electron Beam (EB) Lithography model

A survey of such models [2, 3, 4, 5, 6] in terms of their application-specific nuances, context-specific advantages, deployment-specific limitations, and functional future scopes is discussed in the next section of this text. Based on this discussion, researchers will be able to identify optimum models for their feature-specific use cases. This discussion is followed by section 3, where these models are evaluated & compared in terms of their accuracy, throughput, critical dimensions, deployment cost & computational complexity metrics. This section also proposes evaluation of a novel EB Lithography Optimization Metric (EBLOM), that combines different evaluation metrics, and assists in identification of optimally performing models for different use cases. Finally, this text is concluded with some context-specific observations about the reviewed models, and recommend fusion methods to improve their real-time performance.

2. Literature Review

A wide variety of models are proposed by researchers for optimization of electron beam lithography process, and each of them vary in terms of their internal operating characteristics. The work in [1] focuses on maximizing the electron beam dose for electron beam lithography-based nanopattern transfer. It was thoroughly researched how to best optimize lithographic features using different PMMA e-beam resist thicknesses. Circular dot patterns with good resolution and high aspect ratio are possible at sub-80 nm. An Au template was produced using lift-off for the production of VLS nanostructures. On a patterned Au template, TiO2 nano islands were produced, and their crystallography was investigated using X-ray diffraction. The faces of nano islands are hexagonal.

The most important element influencing electron beam exposure resolution is proximity effect (PE) [2]. By modelling electron scattering using Monte Carlo, this study explores the proximity effect. Methods for correcting the proximity effect that work well are proposed. The proximity effect is influenced by a variety of factors, including pattern design, size, and packing density as well as process conditions, according to theoretical and experimental evidence. Software cannot fix proximity effects; only process conditions and mask design can. The proximity effect is reduced via mask design, process optimization, and software that corrects for proximity effect.

Manufacturing randomly scattered cuts with acceptable throughput and process variation becomes a challenge when several major players in the IC industry switch to 1D gridded designs to enable scaling to sub-20nm nodes [3]. Users can combine the advantages of several techniques for single-layer manufacturing using hybrid lithography (HLith). In order to effectively assign cuts to 193i or E-Beam processes and make the required modifications to cut distribution, researchers suggest a novel method. Researchers create an algorithm employing the forbidden patterns from the optical simulation, represent the redistribution problem as a well-defined ILP problem, and invoke a reliable solution to validate our method. Experimentally, throughput is enhanced by cut redistribution. EBL may be avoided in sparser layers, lowering manufacturing costs.

Electron-beam lithography (EBL) in the manufacture of microwave circuits was optimized using genetic and simplex-downhill (GSD) algorithms. Due to the high dimensionality of the search space, submicrometric structures [4] have complex exposure patterns that are difficult to empirically discover and optimize using linear search methods. SD was first used to resolve the optimization problem. Due to the vast number of factors and intricate topology of the search space, this approach was unable to provide sufficient patterns. GA-optimized structures were not considerably improved by a hybrid approach that used GAs for global search and an SD method for local optimization. There was a fitness function used. Process tolerances are decreased. We investigated the operators for selection, crossover, mutation, and reinsertion. For 100-nm T-gates and asymmetric recess gate designs, the GA successfully anticipated the scanning patterns. By removing the trial-and-error phases, the simulation and optimization tool may shorten EBL response times.

A proposed sub-22 nm technique is electronic beam lithography (EBL), according to [5]. Bypassing the diffraction limit of the current optical lithography technology, EBL directly blasts the required circuit designs onto the silicon. A technical difficulty is low throughput. Each rectangle in typical EBL is projected by a single electrical shot using a beam with a variable form (VSB). It's possible to be slow. Character projection (CP) is an improved EBL technology that uses a stencil to fire many complex patterns simultaneously. Only a few characters may be used due to space limitations. Uncharacterized patterns must be written by VSB. A significant difficulty is figuring out how to load characters onto the CP stencil to speed up processing. Researchers look into overlapping characters in the stencil design for electronic beam lithography. In contrast to past attempts, our method optimizes character selection and stencil placement. Researchers provide a 2-D simulated annealing framework with a look-ahead sequence pair assessment method and a Hamilton-path based iterative methodology for creating 1-D stencils. Researchers can reduce projection time in half when compared to conventional stencil designs without overlapping characters.

Complex hybrid lithography, which combines multiple patterning with e-beam lithography (MP EBL) [6], may enhance pattern resolution as feature size decreases and circuit complexity increases. A minimum vertex deletion K-partition problem is used to define the layout decomposition problem for hybrid lithography. For each stitch candidate, a virtual vertex is inserted between two feature vertices during the conflict graph construction process. For the smallest odd-cycle cover for K = 2, researchers provide a primal-dual method. "Non-cyclable" edges are eliminated using a chain decomposition approach. Researchers provide a random-initialized local search strategy that makes use of the primal-dual solver for K > 2. In comparison to a two-stage approach, our solutions reduce EBL usage by 64.4 percent with double patterning and 38.7 percent with triple patterning.

A thorough examination of the exposure settings for electron beam lithography using the AR7520 negative tone electron beam resist (NTEB) is presented in work in [7]. To lower resist dimensions, researchers enhanced beam voltage, aperture diameter, and resist thickness. Larger beam energies and thicker resist layers result in less efficient energy deposition into the resist layer, which necessitates higher doses to expose a given dot size, according to real data supported by Monte Carlo models of electron scattering. Forward scattered electrons varied from 50 to 170 nm, depending on the dot size and exposure conditions. When larger dimensions were exposed point by point, a reduced backscattering electrons range of 560 nm was observed, correlating the lower doses seen for larger sizes. By using a baking method to strengthen the resist's etch resistance and better exposure conditions, it is possible to repeatedly produce nanometric devices using a simple lift-off approach.

An electron-beam lithography modelling and optimization tool based on Genetic Algorithms (GA) is described in work in [8]. A resampled resist profile's fitness function is the inverse Euclidian distance between it and its objective. Its boundaries are investigated in this research process. The fracas function is wrong and has limited definition for small in-mist profile dentations and/or a large number of resampled chain nodes because of out-of-sync effects. It is proposed to use a different fitness function depending on the confined resist profile region. Both theoretically and experimentally, this function eliminates minute dents from the ideal resist profile. Structure quality is impacted by this improvement.

According to [9], character projection might boost the throughput of E-beam lithography. Its effectiveness depends on well thought-out and optimized stencils. A 2-D Bin-Packing Stencil Optimization (BPSO) heuristic was proposed by Kuang and Young. Researchers found problems with their methods and created a better algorithm that reduces shot counts by almost half. It is necessary to introduce merit frequency/area (f/A) to choose prospective characters and to provide a precise and effective method to evaluate character occupied area prior to placement. Experiments validate the effectiveness of the approach.

To increase the resist's absorbed energy density, an X-ray lithography technology is looked at in [10]. Review topics include X-ray window use, electron-beam energy, wavelength, and X-ray quantum efficiency. For Si or polymer mask membranes without an X-ray window and a small B-window, K-line radiation from an Al or Si source works best. For large Be windows, L-line sources perform well. For polymer film X-ray masks, our laboratories have developed photo and electron-beam lithography procedures. Pros and downsides of using such masks are discussed. Polymer film masks are good at reproducing etched SiO2 patterns.

Work in [11] indicates that hybrid lithography, which combines multiple patterning with EBL, promises to enhance pattern resolution as feature size decreases and circuit complexity increases. A minimum vertex deletion K-partition problem is used to define the layout decomposition problem for hybrid lithography. For each stitch candidate, a virtual vertex is inserted between two feature vertices during the conflict graph construction process. For the minimum odd-cycle cover for K=2, researchers provide a primal-dual (PD) method. "Non-cyclable" edges are eliminated using a chain decomposition approach. Additionally, researchers contrast two PD techniques, one with planarization and the other without. Researchers describe a local search method that regularly applies PD called random initialized local search. In comparison to a two-stage approach, our solutions reduce EBL usage by 65.5 percent with double patterning and 38.7 percent with triple patterning.

The popularity of 1D gridded pattern creation is growing as a result of the resolution limitations of optical lithography [12]. SADP is a well-known 1D printing method. For 1D layouts at 20nm and beyond, SADP with a single trim mask is insufficient. SADP may be supplemented with e-beam lithography. In order to increase the throughput of 1D pattern printing, researchers in this study investigate e-beam shot count reduction subject to limited line end extension limits. A layout may be printed in two different ways using trim mask and e-beam. The first technique is predicated on trim mask and e-beam end cutting. To eliminate unnecessary pieces, trim mask and e-beam are used. ILP is used to develop both methods. Experimental solutions are possible for both ILP formulations. The two production methods for 1D layout are contrasted.

Beyond 10 nm, electron beam lithography (EBL) may be a competitor for IC manufacturing. Avoiding character overlap may help with stencil design and character projection (CP), which has been proposed [13] as a way to increase throughput. Planning a top-level 2D stencil is NP-hard. No polynomial time optimal solution for the crucial phase of 1D row ordering has been discovered. The row ordering problem, an important subroutine in stencil planning, is addressed by researchers with a polynomial time optimal solution. Proof and tests validate the performance and accuracy of our method.

Due to less proximity effects [14], increased resist sensitivity, and reduced substrate damage, low-energy electron beam lithography is a practical next-generation lithography technique for the 21-nm half-pitch node and beyond. Low-energy electron beam lithography systems with larger beam, grid, and dosage are sought for high-throughput manufacturing (LEBL LGD). Dimensional deviation and edge roughness may be increased by electron shot noise. It has a noticeable effect on patterning accuracy. The International Technology Roadmap for Semiconductors' patterning accuracy standards are satisfied while maximizing throughput in this work's innovative approach. It employs an innovative patterning prediction method to precisely quantify the shot noise-induced patterning variability and a mathematical optimization approach to choose the ideal writing settings. The precision and computational effort are balanced using a new patterning prediction approach. The efficiency of the new approach is shown with a static random-access memory circuit. Electrical performance is evaluated using gate-slicing and open transistor models. The static noise margin may be greatly increased, according to numerical results.

Long-range fogging affects contemporary electron-beam lithography (EBL), which results in excessive exposure and layout distortions. The fogging-fighting positioning approach is suggested in this article. The idea is to decrease fogging variation during installation by inserting standard cells, guided by our effective but somewhat accurate fogging effect model, and then to reverse the effects by reducing dosage uniformly throughout the chip. The quick Gauss Transforms and Hermite expansion (GTH) are used by the researchers in [15] to build a foggy source model and an effective, precise evaluation method. The method allows for iterative assessment and variation reduction during global placement while speeding up convolution computation by 30.2 times with just 2.35 percent absolute average faults. Thorough placement and legalization that is fogging-aware increase placement quality and reduce variation in fog. Our method maintains wirelength quality and runtime effectiveness while reducing fogging variation by 35.4%.

A memory-effective method for creating scanning-beam lithography techniques is provided by work in [16]. Finding an exposure pattern that reduces the difference between a desired and anticipated output image is one of these strategies. The number of pixels, which might be millions or billions, is equal to the free variables. In the proposed method, the problem area is divided into overlapping subdomains with restricted boundary constraints, which are addressed sequentially using constrained gradient search (L-BFGS-B). The problem's inherent sparsity and the quick Fourier transform reduce calculation time. In contrast to past strategies, which reduced memory use by the number of subdomains at the price of more computations, researchers may construct a new trade-off between memory consumption and computing time. In a case with 30 million variables, the recommended method reduces memory by 67% while increasing computation time by 27%. The described method may be modified to create focused ion beam deposition, scanning electron beam lithography, and scanning laser lithography.

Using the ZBA23 (Raith) electron beam lithography system, work in [17] evaluated exposed and created negative electron resist AR-N 7520 profiles at various exposure doses and pre-defined exposure patterns. For resist profile cross-sections, a number of geometric quality specifications are provided. Empirical modelling is used to determine how resist profile shape affects exposure dose. With the help of multicriteria optimization, these overall quality indicators are used to provide the technical specifications for newly produced profiles.

Numerous optical technologies and applications use photonic nanostructures [18]. EBL is used to make nanostructures in certain high-end applications. The exposure time for the EBL systems may be more than 24 hours per 1 cm2. To increase EBL writing speed, researchers developed a target-function-based method. As an example, researchers use Fourier Fidelity. Transforming (FFT) the spectra of nanostructures for thin film light trapping will improve the lithography procedure. Without compromising photonic performance, researchers can cut the exposure duration by 5.5. Researchers show that faster written structures are just as effective as the originals. Since the objective function may be altered, the method is applicable to guided mode resonant grating and other fields. These innovations improve EBL and provide potential business applications.

High-resolution nanopatterns must be created using electron-beam lithography (EBL) [19]. Pattern quality is reduced and application performance is impacted by the proximity effect in EBL. In particular for complex and large-area patterns, conventional proximity effect correction (PEC) procedures, which employ cell or route elimination for development simulation, are computationally time-consuming. By converting pattern feasibility into the shortest route problem utilizing critical-development time, the authors propose a short-range PEC strategy. To enhance electron dose distribution in EBL, authors combine this evaluation method with swarm intelligence. The U-shaped split-ring resonator design is made using the PEC algorithm, which also generates an exposure pattern that is optimal and achieves the desired results. Our PEC approach reduces computational costs and is perfect for creating complex patterns with constraints.

The processing, microstructure, and mechanical properties of Ti–6Al–4V E-PBF additive manufacturing were examined in work in [20]. Researchers investigate integrating, consolidating, or repairing the substrate. To investigate the joining behaviour and microstructural characteristics of the bonding region, several starting plate surface conditions are used. The more fragile Ti–6Al–4V substrate experiences mechanical breakdowns as a result of predominating plastic stresses. The hybrid concept is shown through E-PBF fabrication and substrate bonding. This study contributes basic information and improves hybrid E-PBF additive manufacturing.

Work [21] explores the selectivity of hydrogen-silsesquioxane (HSQ) mask-based reactive ion etching of functional materials in nano electronic device topologies. For monocrystalline silicon, metallic Ta layers, dielectric SiO2 layers, Al2O3, HfO2, Si3N4, and low-k organo-silicate glass (OSG) on silicon substrates, the formation of sub-50-nm nanostructures under the HSQ mask is explored. In addition to producing structures with relatively high aspect ratios and absolute layer thicknesses of tens of nanometres, HSQ resist masks may be utilized to fabricate prototypes of micro- and nano-electronic devices with topological dimensions up to 10 nanometres.

Since photolithography has an intrinsic resolution limit, authorities began looking into alternate patterning processes as feature sizes continued to drop quickly [22]. High-resolution production in large quantities is possible using next-generation lithography (NGL). The difficulties and possible paths of NGL are covered in this article. The best solution for sub-10-nm manufacturing is EUVL, which might satisfy commercial demands. EUVL has advanced significantly and will shortly be made available for purchase. Maskless lithography is used in R&D, the manufacture of masks and moulds, and low-volume chip design. In the lab, directed self-assembly has been accomplished; however, NGL still needs further development. The straightforward procedure stages, high throughput, high resolution, and low cost of nanoimprint lithography make it the perfect platform for nanofabrication. There are many obstacles to overcome, and further technological developments are required to make the operations reliable and significant. Finally, several approaches are contrasted.

A novel in situ imaging method and detector array for the focused electron beam are described in work in [23]. (e-beam). A full FinFET CMOS logic compatibility, compact 2 T pixel structure, quick reaction, high responsivity, and wide dynamic range are all features of the in-tool, on-wafer e-beam detector array. Off-line electrical reading is made possible by the sensing/storage node's ability to store the e-beam imaging pattern and detection results without the need for external power. This may be utilized to quickly offer fast feedback on the dose, accelerating energy, and intensity distributions of the e-key beam on the projected wafers.

Manometer-scale manufacturing resolution is possible using electron beam lithography (EBL), according to [24]. Arranged 3D nanostructures cannot be produced using current EBL methods. Function, structural soundness, and resolution are essential. Researchers disclose all-aqueous, high-fidelity production of functional 3d nanostructures at sub-15 nm resolution using their voltage-regulated 3D EBL. Recombinant Spider Silk Proteins (RSSP) may be used as a resist to create nanoscale 3D prints with excellent resolution and durability. Polymorphic spider silk proteins may be shaped at the molecular level by having the ability to define structural transitions with energetic electrons at different depths in a 3D protein matrix. Physiochemical and/or biological functions may be embedded in three-dimensional nanostructures through genetic or mesoscopic manipulation of spider silk proteins. Our method makes it possible to produce functionalized and hierarchically ordered 3D nanocomponents and nanodevices for nanoscale robotics, medicinal devices, and biomimetics quickly and easily.

The small beam interaction volume of the possible lithographic nano structuring technique based on selective exposure of polymer resist by ions (tens of nanometres). The resist is modified by the majority of the beam energy in [25]. It allows for sub-10-nanometer precision, incredible energy economy, and almost little proximity effect. This results in inhomogeneous non-resistance of the absorbed doze and depth-dependent dissolving rate. Thus, the traditional resist contrast method cannot be used. An innovative method for determining resist contrast is provided and used in the current investigation. Its contrast and ion energy were 3.1 and 42 nm, respectively, for PMMA resist exposed to a 30 keV Ga+ ion beam.

Interest in the topology of magnetic skyrmions, which are topological spin textures, has increased [26]. Skyrmions provide information technology with high-density and energy-efficient magnetic memory devices, but its complex topology may also give rise to intriguing physical phenomena as chiral magnon and skyrmion glass states. The key to enhancing topological magnetism is large-scale generation of skyrmions and control of their patterns. In exchange-biased magnetic multilayers, a brand-new, universal method is shown for "printing" zero-field stable skyrmions in any design. Utilizing the potential for local thermal excitations to rearrange antiferromagnetic order, skyrmion lithography employs a focused electron beam and a graphic pattern generator to "print" skyrmions. This method opens the door for topological magnetism study by allowing the creation of arbitrary skyrmion patterns.

Zinc oxide (ZnO) has been investigated for use in large-area electronics, and solution-processing technologies show promise for producing the material at a low cost [27]. There is presently little research on top-down manufacturing processes with nanoscale resolution. The DW-EBL of solution precursors is described in this study as negative tone resists, which are then processed appropriately to create micron/nano-FETs (FETs). ZnO FET mobility and current density increase by two orders of magnitude when the precursor pattern width is decreased from 50 m to 100 nm. These nano-FETs exhibit the greatest on-state current densities for direct-write precursor-patterned nanoscale ZnO FETs, 10 A m1, and field-effect mobilities of 30 cm2 V1 s1. Atomic force microscopy and parametric modelling are used to investigate the reason for the rise in device performance. The findings show how pre-decomposition nanoscale precursor patterning affects the morphological evolution of ZnO grains and provide possibilities for large-scale integration and shrinking of solution-processed nanoscale oxide FETs.

According to [28], self-organized semiconductor quantum dots are ideal two-level systems with uses in photonic quantum technology. For instance, as emitters in almost perfect quantum light sources. Ultra-stable singlet-triplet spin qubits enabling effective spin-photon interfaces and deterministic photonic 2D cluster-state generation may be hosted by coupled quantum dot systems with considerably increased functionality. A QDM device has excellent optical characteristics. Pin-diode layers of electrically controlled QDMs are used. QDMs are integrated into a photonic structure with a circular Bragg grating using in situ electron beam lithography. A photon extraction efficiency of 244% is measured, which is in great accord with computer simulations. Theoretically controlled orbital couplings and charge state of QDMs are shown via bias voltage dependent spectroscopy. Single-photon emission and multi-photon suppression are well-controlled by QDM devices. Due to these qualities, QDM devices are promising foundational components for next nanophotonic photonic quantum networks.

Work in [29] claims that plasmonics is driven by advances in micro- and nanofabrication. Many experimental design ideas challenge the limitations of production techniques. A practical method for creating intricate plasmonic nanostructures is to combine gold ion-beam and electron-beam lithography. The approach is applicable to both 2D and 3D nanostructures. There are large, flawlessly realistic creations on display. These structures have precise form and alignment. In order to produce complex plasmonic structures with superior optical properties and functionalities as well as ultra-distinct spectral features for use in plasmonics, nanooptics, meta-surfaces, plasmonic sensing, and other areas, the two techniques are combined in a way that fully exploits their complementary strengths.

Although technique is impracticable for large microstructure arrays, patterning with a focused ionizing radiation beam offers excellent spatial accuracy [30]. To create sub micropores in low-sensitivity polyethylene terephthalate, researchers advise adjusting x-ray lithography settings. Above a large substrate area, this optimization generates micropores with a high aspect ratio (over 20) and diameters as large as 0.4 m. (up to several square centimetres).

High-resolution circuit patterning is accomplished in [31] using e-beam lithography. Nearby areas are made visible as a result of electron scattering in the resist and substrate. They limit the resolution of lithography. Numerous modelling and correction techniques were attempted since these effects may be mathematically described. The suggested methods provide precision for printing circuit layouts but require a significant amount of computational work. Modern GPGPUs are as powerful as a small cluster and feature hundreds of processing cores. Correction algorithms may be powered by GPGPUs. Using GPGPUs, researchers evaluate a short-range proximity effect correction method.

According to [32], precise nanoscale structures may be made using electron-beam lithography (EBL). As resolution becomes closer to the electron beam's focal point in thick resist layers, dose insufficiency occurs. The best area dosage for writing small features is assigned using study, a theory for comprehending and adjusting this behaviour, and a method. The proximity effect results in an insufficiency of dosage by dispersing energy in bigger resist volumes than desired. A fundamental spread interpretation was used to create the proximity effect correction (PEC) approach. Researchers were able to produce superior nanostructures using 50 kV EBL on AR-P 6200 (CSAR 62) resist. This entails quick, affordable exposures that work with later processes.

Traditional electron beam lithography (EBL) is a "blind" open-loop method since there isn't enough input; the exposed pattern is checked after ex situ resist production, when it's too late to make improvements. In situ feedback on e-beam distortion and enlargement may be used using self-developing nitrocellulose resist (SNR) [33], whose pattern manifests after exposure without ex situ development. Researchers exposed the same test patterns in nitrocellulose at several locations around the writing field, examined them there, and then changed the beam's (working distance) distance accordingly. The process was maintained until the disclosed pattern's size and shape were uniform across the writing area. Researchers exposed PMMA after employing nitrocellulose resist to optimize the beam. In comparison to 210 nm without beam modification, researchers were able to achieve 80-nm resolution across a 1 mm by 1 mm writing area.

In order to assess PMMA resist and improve EBL nano-patterning resolution, research employing mathematical modeling and process simulation tools (CASINO, TREM, SELID) is detailed in [34]. To gather EBL data, many approaches are employed (energy deposition function, proximity effect parameters, solubility rate, etc). (Regression models, Monte Carlo techniques, etc.).

The research in [35] examines the FEBID's physical foundations, applications, and future possibilities. FEBID is a single-step direct-write nanolithography technique that breaks down precursor gas molecules using an electron beam the size of a manometer. A gas injector in a scanning electron microscope is used for the technique.

To replicate and enhance electron beam lithography, Hunan University (HNU) developed HNU-EBL [36]. (EBL). Three modules make up it. The point spread function (PSF) is fitted after the Monte Carlo (MC) simulation of the electron pathways in the EBL resist and substrate layers. In order to address closeness and fogging effects that could impair the accuracy and pattern quality of lithography, PSF improves electron dose distribution using the fast Fourier transform (FFT). Third, measures like edge placement inaccuracy are used to evaluate the quality of the optimized pattern (EPE). HNU-EBL enhances nm-scale device fabrication by simulating sub-10 nanometre EBL.

Although its successive heating process may result in CD distortion, electron beam lithography (EBL) has been used to manufacture high-resolution photomasks [37]. To lessen heating and CD distortion, subfield scheduling, which rearranges subfields during writing, is required. This paper illustrates a traveling salesman problem with limited maximum–minimum m-neighbours and blocked areas (called constrained m-nTSP). Researchers divide a constrained m-nTSP into smaller issues conforming to a specific instance with points on two parallel lines, answer each issue using a proven superior linear-time approximation method, and then combine them into a comprehensive scheduling solution. To increase EBL writing speed and minimize heating, our method may result in shorter distances between subsequent subfields. It is feasible to save between 10% and 14% more temperature and distance than the state-of-the-art for a variety of applications.

The production of photomasks using electron beam lithography (EBL) has shown tremendous promise, but the CD distortion that might result from the method's repeated heating is a concern. To avoid writing adjacent subfields sequentially, subfield scheduling [38] is crucial. Writing in one location might heat up nearby spaces and prevent writing in others. The subfield scheduling problem is addressed for the first time in this study while taking blocked regions into account (constrained MSTSP). The problem is solved optimally in linear time using a special case of restricted MSTSP with points on two parallel lines. Researchers divide the constrained MSTSP into subproblems that correspond to the particular instance, optimally and efficiently solve each subproblem, and then merge the sub solutions into a complete scheduling solution. Results from experiments show that our method is effective and efficient in finding optimal subfield scheduling options for e-beam photomask manufacturing processes.

According to [39], a primary cause of CD distortion in the creation of electron beam photomasks is resist heating. Reduced resist heating-related CD variation is achieved by using lower beam currents, longer times between electron flashes, and many passes. All of these techniques hinder mask writing. The semiconductor industry's productivity is constrained by rising mask writing expenses. For reducing CD distortion from resist heating, researchers look at a new level of flexibility. CD variability brought on by resist heating may be decreased without lengthening mask writing time by optimizing subfield writing sequence.

CD distortion results from resist heating during high-voltage, high-throughput electron beam e-beam mask writing [40]. Reticule heating too much changes resist sensitivity, resulting in CD variation. Reticulate CD distortions on the wafer are enlarged by MEEF. In sub-90 nm devices, CD variation has an impact on performance, performance variation, and product yield. CD distortion is decreased via repeated pass writing, longer electron flash delays, and decreased e-beam current density. These methods together lower the throughput of mask writing, which lowers productivity in the semiconductor sector. Researchers provide a method to reduce CD distortion and improve mask writing efficiency. By planning subfields, researchers improve the sequence of mask writing and e-beam current density. By evaluating resist temperature quickly analytically, researchers schedule subfields. Simulations show that, while maintaining the same mask writing productivity, the innovative subfield scheduling scheme may reduce the maximum resist temperature by 12°C. Larger beam current densities may be possible with improved subfield scheduling, boosting writing throughput without compromising CD control levels. Thus, based on this detailed discussion it can be observed that these models vary in terms of their applicability performance, and can be used depending upon application-specific requirements. To further simplify the process of selection for EBL Models, next section compares them in terms of their performance-specific parameters, which include, accuracy of processing, computational complexity, cost of deployment, delay needed for processing, and scalability measures, which will assist readers in selection of models in terms of their qualitative performance metrics for multiple use cases.

3. Pragmatic Analysis

After conducting a comprehensive analysis of the different EBL Optimization Models that are now in use, it was found that these models exhibit a great deal of diversity in terms of their internal operational features. Therefore, in order to aid readers in identifying the EBL models that are optimal, this section compares several aspects of each of those models. These include, their accuracy of processing (A), computational delay (D), scalability (S), deployment cost (DC), and computational complexity (CC) parameters. These parameters were quantized into Low Value Range (LVR=1), Medium Value Range (MVR=2), High Value Range (HVR=3), and Very High Value Range (VHVR=4), as per their internal module deployment characteristics. Based on this evaluation strategy, the comparison can be observed from table 1 as follows,

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

Table 1. Performance evaluation of different EBL Optimization models

Based on this evaluation, it can be observed that GA [8], BPSO [9], MN TSP [37], and MSTSP [38] have higher accuracy, thus can be used for high-performance EBL applications. Based on table 1, it can also be observed that GA [8], BPSO [9], SNR [33], MN TSP [37], and MSTSP [38] have lower complexity, thus can be used for EBL applications that have low-performance computing capabilities. Similarly, based on table 1, it can also be observed that GA [8], BPSO [9], ZBA23 [17], RSSP [24], and MN TSP [37] have lower delay, thus can be used for high-speed EBL applications. Similarly, based on table 1, it can also be observed that GA [8], ZBA23 [17], FFT [36], and MSTSP [38], have deployment costs, thus can be used for low-cost EBL applications. Similarly, based on table 1, it can also be observed that GA [8], BPSO [9], FFT [36], MN TSP [37], and MSTSP [38] have higher scalability, thus can be used for highly scalable EBL applications. These metrics were combined to form a novel EBL Optimization Metric (EBLOM), which can be evaluated from equation 1,

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

Based on this evaluation, it can be observed that GA [8], BPSO [9], MN TSP [37], MSTSP [38], FFT [36], RSSP [24], ZBA23 [17], DW-EBL [27], CP [13], and FFT [18] showcase better EBL performance, thus, can be used for high accuracy, low delay, low complexity, low cost & high scalability data EBL application scenarios. Based on this evaluation, researchers can identify optimum models for their application-specific & performance-specific EBL applications.

4. Conclusion

This text initially discusses in-depth characteristics of different EBL optimization Models, and evaluates them in terms of their deployment-specific nuances, contextual advantages, application-specific limitations, and functional future scopes. Based on this discussion it was observed that bioinspired models outperform other models in terms of function operations, thus must be used for multiple EBL optimization scenarios. The internal performance characteristics of these models were compared, and it was found that GA, BPSO, MN TSP, and MSTSP have higher accuracy. On the other hand, GA, BPSO, SNR, MN TSP, and MSTSP have lower complexity, which means that they can be used for high-accuracy EBL applications that have low-performance computing capabilities. Although it was shown that GA, BPSO, ZBA, RSSP, and MN TSP have reduced latency, in addition, GA, ZBA, FFT, and MSTSP have deployment costs, and thus they are able to be employed for high-speed and low-cost EBL applications. In a similar vein, it was also discovered that GA, BPSO, FFT, MN TSP, and MSTSP have superior scalability, and as a result, they are suitable for usage in highly scalable EBL applications. These metrics were combined to form an EBL Optimization Metric, which indicated that GA, BPSO, MN TSP, MSTSP, FFT, RSSP, ZBA, DW-EBL, CP, and FFT showcase better overall performance and, as a result, can be utilized for high accuracy, low delay, low complexity, low cost, and high scalability data EBL application scenarios. Researchers are able to develop optimal models for their application-specific and performance-specific EBL applications based on the findings of this examination. In the future, researchers will be able to improve the performance of these models by using a combination of different bioinspired methodologies and then fusing those techniques together to tackle a variety of different objective problems. In addition, researchers may combine Convolutional Neural Networks (CNNs) and other deep learning and machine learning models. This gives them the ability to enhance EBL characteristics for improved pre-emptive performance optimization in a variety of use case situations.

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