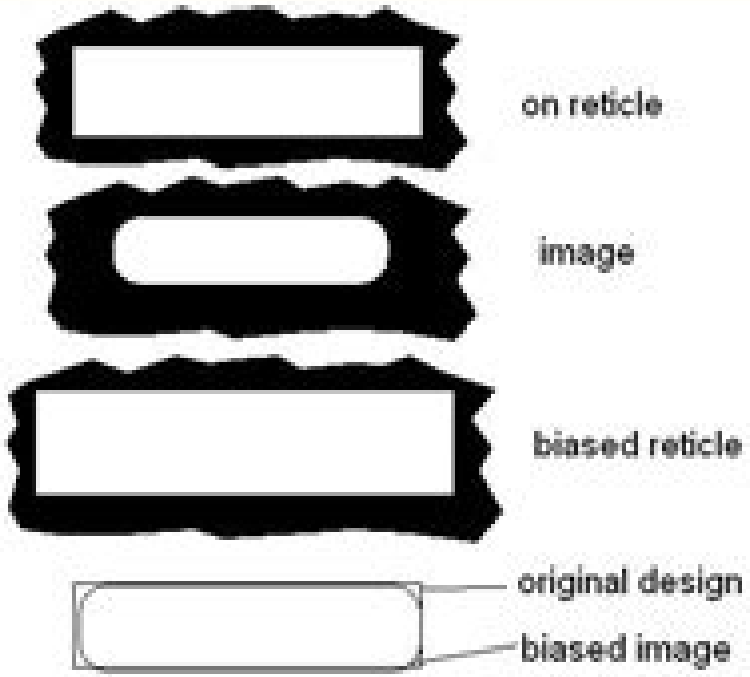
Resolution Enhancement Techniques (RETs)

Linewidth biasing



Earliest form of optical proximity compensation,

Improves pattern fidelity, but not increasing resolution or contrast

Should use *Imaging Enhancement Techniques* rather than RETs

Resolution Enhancement Techniques In Optical Lithography

Yoshio Nishi,Robert Doering

Resolution Enhancement Techniques In Optical Lithography:

Resolution Enhancement Techniques in Optical Lithography Alfred Kwok-Kit Wong,2001 Ever smaller IC devices are pushing the optical lithography envelope increasing the importance of resolution enhancement techniques This tutorial encompasses two decades of research It discusses theoretical and practical aspects of commonly used techniques including optical imaging and resolution modified illumination optical proximity correction alternating and attenuating phase shifting masks selecting RETs and second generation RETs Useful for students and practicing lithographers *Selected Papers on Resolution Enhancement Techniques in Optical Lithography* F. M. Schellenberg,2004 Optical lithography for integrated circuits is undergoing a renaissance with the adoption of Resolution Enhancement Technology RET Some RET concepts have become routine in manufacturing This volume gathers together seminal RET papers **Design and Development of Material-based Resolution Enhancement Techniques for Optical Lithography** Xinyu Gu,2011 The relentless commercial drive for smaller faster and cheaper semi conductor devices has pushed the existing patterning technologies to their limits Photolithography one of the crucial processes that determine the feature size in a microchip is currently facing this challenge The immaturity of next generation lithography NGL technology particularly EUV forces the semiconductor industry to explore new processing technologies that can extend the use of the existing lithographic method i e ArF lithography to enable production beyond the 32 nm node Two new resolution enhancement techniques double exposure lithography DEL and pitch division lithography PDL were proposed that could extend the resolution capability of the current lithography tools This thesis describes the material and process development for these two techniques DEL technique requires two exposure passes in a single lithographic cycle The first exposure is performed with a mask that has a relaxed pitch and the mask is then shifted by half pitch and re used for the second exposure The resolution of the resulting pattern on the wafer is doubled with respect to the features on the mask This technique can be enabled with a type of material that functions as optical threshold layer OTL The key requirements for materials to be useful for OTL are a photoinduced isothermal phase transition and permeance modulation with reverse capabilities A number of materials were designed and tested based on long alkyl side chain crystalline polymers that bear azobenzene pendant groups on the main chain The target copolymers were synthesized and fully characterized A proof of concept for the OTL design was successfully demonstrated with a series of customized analytical techniques PDL technique doubles the line density of a grating mask with only a single exposure and is fully compatible with current lithography tools Thus this technique is capable of extending the resolution limit of the current ArF lithography without increasing the cost of ownership Pitch division with a single exposure is accomplished by a dual tone photoresist This thesis presents a novel method to enable a dual tone behavior by addition of a photobase generator PBG into a conventional resist formulation The PBG was optimized to function as an exposure dependent base quencher which mainly neutralizes the acid generated in high dose regions but has only a minor influence in

low dose regions The resulting acid concentration profile is a parabola like function of exposure dose and only the medium exposure dose produces a sufficient amount of acid to switch the resist solubility This acid response is exploited to produce pitch division patterns by creating a set of negative tone lines in the overexposed regions in addition to the conventional positive tone lines A number of PBGs were synthesized and characterized and their decomposition rate constants were studied using various techniques Simulations were carried out to assess the feasibility of pitch division lithography It was concluded that pitch division lithography is advantageous when the process aggressiveness factor k1 is below 0 27 Finally lithography evaluations of these dual tone resists demonstrated a proof of concept for pitch division lithography with 45 nm pitch divided line and space patterns for a k1 of 0 13 **Selected Papers on Resolution Enhancement Techniques in Optical Lithography** F. M. Schellenberg,2004-03-30 Optical lithography for integrated circuits is undergoing a renaissance with the adoption of resolution enhancement techniques RET Some RET concepts have become routine in manufacturing almost two decades after the original applications were conceived This volume gathers together seminal RET papers Since many of the first applications were announced by Japanese authors well before the material was presented in English some of the original Japanese papers are included plus their English translations **Optimization of Resolution Enhancement Techniques in Optical Lithography** ,2009 As todays semiconductor fabrication industry tries to keep up with Moore s Law which predicts the downscaling of integrated circuit size and the doubling of transistor counts every two years resolution enhancement techniques RET play a much more important role than anytime in the past Optical proximity correction OPC phase shifting mask PSM and off axis illumination OAI are RETs used extensively in the semiconductor industry to improve the resolution and pattern fidelity of optical lithography Preserving the fidelity of the circuit patterns is important for preserving the performance predicted in the design stage of the integrated circuit IC Typical circuit patterns exhibit regular geometries such as lines L joint U joint and so on These regular geometries reduce the resistances between nodes and simplify the process of routing In the past decades a variety of OPC PSM and illumination design approaches have been proposed in the literature In general these approaches are divided into two subsets rule based and model based approaches This dissertation focuses on the study and development of model based OPC PSM and illumination optimization approaches for both coherent imaging systems and partially coherent imaging systems For coherent imaging systems we develop generalized gradient based RET optimization methods to solve for the inverse lithography problem where the search space is not constrained to a finite phase tessellation but where arbitrary search trajectories in the complex space are allowed Subsequent mask quantization leads to efficient design of PSMs having an arbitrary number of discrete phases In order to influence the solution patterns to have more desirable manufacturability properties a wavelet regularization framework is introduced offering more localized flexibility than total variation regularization methods traditionally employed in inverse problems The algorithms provide highly effective four phase PSMs capable of generating mask patterns with arbitrary

Manhattan geometries Furthermore a double patterning optimization method for generalized inverse lithography is developed where each patterning uses an optimized two phase mask These algorithms are computationally efficient however they focused on coherent illumination systems Most practical illumination sources have a nonzero line width and their radiation is more generally described as partially coherent Partially coherent illumination PCI is desired since it can improve the theoretical resolution limit PCI is thus introduced in practice through modified illumination sources having large coherent factors or through off axis illumination In partially coherent imaging the mask is illuminated by light travelling in various directions The source points giving rise to these incident rays are incoherent with one another such that there is no interference that could lead to nonuniform light intensity impinging on the mask The gradient based inverse lithography optimization methods derived under the coherent illumination assumption fail to account for the nonlinearities of partially coherent illumination and thus perform poorly in the partially coherent scenario For partially coherent imaging systems with inherent nonlinearities the sum of coherent systems SOCS model and the average coherent approximation model are applied to develop effective and computationally efficient OPC optimization algorithms for inverse lithography Wavelet regularization is added to the optimization framework to reduce the complexity of the optimized masks Subsequently a Singular Value Decomposition SVD model is used to develop computationally efficient PSM optimization algorithms for inverse lithography A novel DCT post processing is proposed to cut off the high frequency components in the optimized PSMs and keep the fabricating simplicity Furthermore a photoresist tone reversing technique is exploited in the design of PSMs to project extremely sparse patterns As traditional RETs the above mentioned gradient based inverse OPC and PSM optimization methods fix the source thus limiting the degrees of freedom during the optimization of the mask patterns To overcome this restriction computationally efficient pixel based simultaneous source mask optimization SMO methods for both OPC and PSM designs are developed in this dissertation The synergy is exploited in the joint optimization of source and mask patterns The resulting source and mask patterns fall well outside the realm of known design forms In these SMO algorithms the Fourier series expansion model is applied to approximate the partially coherent system as a sum of coherent systems Cost sensitivity is used to drive the output pattern error in the descent direction In order to influence the solution patterns to have more desirable manufacturability properties topological constraints are added to the optimization framework Several illustrative simulations are presented to demonstrate the effectiveness of the proposed algorithms The above gradient based inverse lithography optimization approaches are effective and computationally efficient under the thin mask assumption where the mask is considered as a 2 D object As the critical dimension CD printed on the wafer shrinks into the subwavelength regime the thick mask effects become prevalent and thus these effects must be taken into account Thus OPC and PSM methods derived under the thin mask assumption have the inherent limitations and perform poorly in the subwavelength scenario In order to overcome this limitation the final contribution of this dissertation focuses on developing OPC and PSM optimization

methods based on the boundary layer BL model to take into account the thick mask effects Attributed to the nonlinear properties of the BL model model based forward lithography methods are exploited to obtain the optimized binary and phase shifting masks The advantages and limitations of the proposed algorithm are discussed and several illustrative simulations are presented *Resolution Enhancement Techniques in Deep UV Optical Lithography for the 90nm Silicon Technological Node and Below* Gianfranco Capetti,2005 *Physics of Semiconductor Devices* Vikram Kumar,Prasanta Kumar Basu,2002

Handbook of Photomask Manufacturing Technology Syed Rizvi,2018-10-03 As the semiconductor industry attempts to increase the number of functions that will fit into the smallest space on a chip it becomes increasingly important for new technologies to keep apace with these demands Photomask technology is one of the key areas to achieving this goal Although brief overviews of photomask technology exist in the literature the Handbook of Photomask Manufacturing Technology is the first in depth comprehensive treatment of existing and emerging photomask technologies available The Handbook of Photomask Manufacturing Technology features contributions from 40 internationally prominent authors from industry academia government national labs and consortia These authors discuss conventional masks and their supporting technologies as well as next generation non optical technologies such as extreme ultraviolet electron projection ion projection and x ray lithography The book begins with an overview of the history of photomask development It then demonstrates the steps involved in designing producing testing inspecting and repairing photomasks following the sequences observed in actual production The text also includes sections on materials used as well as modeling and simulation Continued refinements in the photomask making process have ushered in the sub wavelength era in nanolithography This invaluable handbook synthesizes these refinements and provides the tools and possibilities necessary to reach the next generation of microfabrication technologies Electronic Design Automation for IC Implementation, Circuit Design, and Process Technology Luciano Lavagno,Igor L. Markov,Grant Martin,Louis K. Scheffer,2017-02-03 The second of two volumes in the Electronic Design Automation for Integrated Circuits Handbook Second Edition Electronic Design Automation for IC Implementation Circuit Design and Process Technology thoroughly examines real time logic RTL to GDSII a file format used to transfer data of semiconductor physical layout design flow analog mixed signal design physical verification and technology computer aided design TCAD Chapters contributed by leading experts authoritatively discuss design for manufacturability DFM at the nanoscale power supply network design and analysis design modeling and much more New to This Edition Major updates appearing in the initial phases of the design flow where the level of abstraction keeps rising to support more functionality with lower non recurring engineering NRE costs Significant revisions reflected in the final phases of the design flow where the complexity due to smaller and smaller geometries is compounded by the slow progress of shorter wavelength lithography New coverage of cutting edge applications and approaches realized in the decade since publication of the previous edition these are illustrated by new chapters on 3D circuit integration and clock design Offering improved depth

and modernity Electronic Design Automation for IC Implementation Circuit Design and Process Technology provides a valuable state of the art reference for electronic design automation EDA students researchers and professionals

Handbook of Optical Systems, Volume 2 Wolfgang Singer,Michael Totzeck,Herbert Gross,2006-05-12 The state of the art full colored handbook gives a comprehensive introduction to the principles and the practice of calculation layout and understanding of optical systems and lens design Written by reputed industrial experts in the field this text introduces the user to the basic properties of optical systems aberration theory classification and characterization of systems advanced simulation models measuring of system quality and manufacturing issues In this Volume Volume 2 continues the introduction given in volume 1 with the more advanced texts about the foundations of image formation Emphasis is placed on an intuitive while theoretically exact presentation More than 400 color graphs and selected references on the end of each chapter support this undertaking From the contents 17 Wave equation 18 Diffraction 19 Interference and coherence 20 Imaging 21 Imaging with partial coherence 22 Three dimensional imaging 23 Polarization 24 Polarization and optical imaging A1 Mathematical appendix Other Volumes Volume 1 Fundamentals of Technical Optics Volume 3 Aberration Theory and Correction of Optical Systems Volume 4 Survey of Optical Instruments Volume 5 Advanced Physical Optics

Nanofabrication Zheng Cui,2009-01-01 Nanofabrication Principles Capabilities and Limits presents a one stop description at the introductory level on most technologies that have been developed which are capable of making structures below 100nm Principles of each technology are introduced and illustrated with minimum mathematics involved The capabilities of each technology in making sub 100nm structures are described The limits of preventing a technology from further going down the dimensional scale are analyzed Drawing upon years of practical experience and using numerous examples Zheng Cui covers state of the art technologies in nanofabrication including Photon based lithography Charged particle beams lithography Nanofabrication using scanning probes Nanoscale replication Nanoscale pattern transfer Indirect nanofabrication Nanofabrication by self assembly Nanofabrication Principles Capabilities and Limits will serve as a practical guide and first hand reference for researchers and practitioners working in nanostructure fabrication and also provides a tool box of various techniques that can be easily adapted in different fields of applications Written for Nanoscience and nanotechnology researchers and engineers technical professionals and academic researchers in the fields of electrtonics mechanical engineering and chemical engineering Laser Beam Shaping Applications Fred M. Dickey,Todd E. Lizotte,Scott C. Holswade,David L. Shealy,2018-10-03 The practice of shaping the irradiance profile of laser beams goes back more than three decades and the applications of beam shaping are as diverse as they are numerous However until Dickey and Holswade s groundbreaking and highly popular Laser Beam Shaping Theory and Techniques was published there was no single detailed treatment available on the underlying theory and basic techniques of beam shaping Building on the foundations of this previous work these esteemed editors have teamed with recognized expert David L Shealy to produce the

first in depth account of beam shaping applications and design Laser Beam Shaping Applications details the important features of beam shaping and exposes the subtleties of the theory and techniques that are best demonstrated through proven applications In chapters contributed by prominent active leaders in their respective specialties the book discusses applications in lithography laser printing optical data storage stable isotope separation adaptive mirrors and spatially dispersive lasers The contributors share major insights knowledge and experience reveal the advantages of the technologies and include extensive references to the literature The book concludes with a summary of beam shaping theory and techniques as well as the history of the field Providing practical expertise Laser Beam Shaping Applications is an extremely helpful guide to improving current laser processes optimizing application specific technologies and advancing future development in the field **Handbook of Semiconductor Manufacturing Technology** Yoshio Nishi,Robert Doering,2017-12-19 Retaining the comprehensive and in depth approach that cemented the bestselling first edition s place as a standard reference in the field the Handbook of Semiconductor Manufacturing Technology Second Edition features new and updated material that keeps it at the vanguard of today s most dynamic and rapidly growing field Iconic experts Robert Doering and Yoshio Nishi have again assembled a team of the world s leading specialists in every area of semiconductor manufacturing to provide the most reliable authoritative and industry leading information available Stay Current with the Latest Technologies In addition to updates to nearly every existing chapter this edition features five entirely new contributions on Silicon on insulator SOI materials and devices Supercritical CO2 in semiconductor cleaning Low dielectrics Atomic layer deposition Damascene copper electroplating Effects of terrestrial radiation on integrated circuits ICs Reflecting rapid progress in many areas several chapters were heavily revised and updated and in some cases rewritten to reflect rapid advances in such areas as interconnect technologies gate dielectrics photomask fabrication IC packaging and 300 mm wafer fabrication While no book can be up to the minute with the advances in the semiconductor field the Handbook of Semiconductor Manufacturing Technology keeps the most important data methods tools and techniques close at hand

Micro/Nanolithography Jagannathan Thirumalai,2018-05-02 The main objective of this book is to give proficient people a comprehensive review of up to date global improvements in hypothetical and experimental evidences perspectives and prospects of some newsworthy instrumentation and its numerous technological applications for a wide range of lithographic fabrication techniques The present theme of this book is concomitant with the lithographic ways and means of deposition optimization parameters and their wide technological applications This book consists of six chapters comprehending with eminence of lithography fabrication and reproduction of periodic nanopyramid structures using UV nanoimprint lithography for solar cell applications large area nanoimprint lithography and applications micro nanopatterning on polymers OPC under immersion lithography associated to novel luminescence applications achromatic Talbot lithography ATL and the soft X ray interference lithography Individual chapters provide a base for a wide range of readers from different fiels students and

researchers who may be doing research pertinent to the topics discussed in this book and find basic as well as advanced principles of designated subjects related to these phenomena explained plainly The book contains six chapters by experts in different fields of lithographic fabrication and technology from over 15 research institutes across the globe **Plasma Processing of Nanomaterials** R. Mohan Sankaran,2017-12-19 We are at a critical evolutionary juncture in the research and development of low temperature plasmas which have become essential to synthesizing and processing vital nanoscale materials More and more industries are increasingly dependent on plasma technology to develop integrated small scale devices but physical limits to growth and other challenges threaten progress Plasma Processing of Nanomaterials is an in depth guide to the art and science of plasma based chemical processes used to synthesize process and modify various classes of nanoscale materials such as nanoparticles carbon nanotubes and semiconductor nanowires Plasma technology enables a wide range of academic and industrial applications in fields including electronics textiles automotives aerospace and biomedical A prime example is the semiconductor industry in which engineers revolutionized microelectronics by using plasmas to deposit and etch thin films and fabricate integrated circuits An overview of progress and future potential in plasma processing this reference illustrates key experimental and theoretical aspects by presenting practical examples of Nanoscale etching deposition of thin films Catalytic growth of carbon nanotubes and semiconductor nanowires Silicon nanoparticle synthesis Functionalization of carbon nanotubes Self organized nanostructures Significant advances are expected in nanoelectronics photovoltaics and other emerging fields as plasma technology is further optimized to improve the implementation of nanomaterials with well defined size shape and composition Moving away from the usual focus on wet techniques embraced in chemistry and physics the author sheds light on pivotal breakthroughs being made by the smaller plasma community Written for a diverse audience working in fields ranging from nanoelectronics and energy sensors to catalysis and nanomedicine this resource will help readers improve development and application of nanomaterials in their own work About the Author R Mohan Sankaran received the American Vacuum Society s 2011 Peter Mark Memorial Award for his outstanding contributions to tandem plasma synthesis *Extending Moore's Law through Advanced Semiconductor Design and Processing Techniques* Wynand Lambrechts,Saurabh Sinha,Jassem Ahmed Abdallah,Jaco Prinsloo,2018-09-13 This book provides a methodological understanding of the theoretical and technical limitations to the longevity of Moore s law The book presents research on factors that have significant impact on the future of Moore s law and those factors believed to sustain the trend of the last five decades Research findings show that boundaries of Moore s law primarily include physical restrictions of scaling electronic components to levels beyond that of ordinary manufacturing principles and approaching the bounds of physics The research presented in this book provides essential background and knowledge to grasp the following principles Traditional and modern photolithography the primary limiting factor of Moore s law Innovations in semiconductor manufacturing that makes current generation CMOS processing possible Multi disciplinary

technologies that could drive Moore s law forward significantly Design principles for microelectronic circuits and components that take advantage of technology miniaturization The semiconductor industry economic market trends and technical driving factors The complexity and cost associated with technology scaling have compelled researchers in the disciplines of engineering and physics to optimize previous generation nodes to improve system on chip performance This is especially relevant to participate in the increased attractiveness of the Internet of Things IoT This book additionally provides scholarly and practical examples of principles in microelectronic circuit design and layout to mitigate technology limits of previous generation nodes Readers are encouraged to intellectually apply the knowledge derived from this book to further research and innovation in prolonging Moore s law and associated principles Computational Lithography Xu Ma,Gonzalo R. Arce,2011-01-06 A Unified Summary of the Models and Optimization Methods Used in Computational Lithography Optical lithography is one of the most challenging areas of current integrated circuit manufacturing technology The semiconductor industry is relying more on resolution enhancement techniques RETs since their implementation does not require significant changes in fabrication infrastructure Computational Lithography is the first book to address the computational optimization of RETs in optical lithography providing an in depth discussion of optimal optical proximity correction OPC phase shifting mask PSM and off axis illumination OAI RET tools that use model based mathematical optimization approaches The book starts with an introduction to optical lithography systems electric magnetic field principles and the fundamentals of optimization from a mathematical point of view It goes on to describe in detail different types of optimization algorithms to implement RETs Most of the algorithms developed are based on the application of the OPC PSM and OAI approaches and their combinations Algorithms for coherent illumination as well as partially coherent illumination systems are described and numerous simulations are offered to illustrate the effectiveness of the algorithms In addition mathematical derivations of all optimization frameworks are presented The accompanying MATLAB software files for all the RET methods described in the book make it easy for readers to run and investigate the codes in order to understand and apply the optimization algorithms as well as to design a set of optimal lithography masks The codes may also be used by readers for their research and development activities in their academic or industrial organizations An accompanying MATLAB software guide is also included An accompanying MATLAB software guide is included and readers can download the software to use with the guide at ftp ftp wiley com public sci_tech_med computational_lithography Tailored for both entry level and experienced readers Computational Lithography is meant for faculty graduate students and researchers as well as scientists and engineers in industrial organizations whose research or career field is semiconductor IC fabrication optical lithography and RETs Computational lithography draws from the rich theory of inverse problems optics optimization and computational imaging as such the book is also directed to researchers and practitioners in these fields **Microoptics and Nanooptics Fabrication** Shanalyn Kemme,2018-09-03 The deep interconnection between micro nanooptical components and related

fabrication technologies and the constant changes in this ever evolving field means that successful design depends on the engineer s ability to accommodate cutting edge theoretical developments in fabrication techniques and experimental realization Documenting the state of the art in fabrication processes Microoptics and Nanooptics Fabrication provides an up to date synopsis of recent breakthroughs in micro and nanooptics that improve key developmental processes This text elucidates the precise and miniaturized scale of today s fabrication methods and their importance in creating new optical components to access the spectrum of physical optics It details successful fabrication techniques and their direct effect on the intended performance of micro and nanooptical components The contributors explore the constraints related to material selection component lateral extent minimum feature size and other issues that cause fabrication techniques to lag behind corresponding theory in the development process Written with the professional optical engineer in mind this book omits the already well published broader processing fundamentals Instead it focuses on key tricks of the trade helpful in reformulating processes to achieve necessary optical targets improve process fidelity and reduce production costs The contributing authors represent the vanguard in micro optical fabrication The result of their combined efforts this searing analysis of emerging fabrication technologies will continue to fuel the expansion of optics components from the microwave to the infrared through the visible regime **Handbook of Integrated Circuit Industry** Yangyuan Wang,Min-Hwa Chi,Jesse Jen-Chung Lou,Chun-Zhang Chen,2023-11-27 Written by hundreds experts who have made contributions to both enterprise and academics research these excellent reference books provide all necessary knowledge of the whole industrial chain of integrated circuits and cover topics related to the technology evolution trends fabrication applications new materials equipment economy investment and industrial developments of integrated circuits Especially the coverage is broad in scope and deep enough for all kind of readers being interested in integrated circuit industry Remarkable data collection update marketing evaluation enough working knowledge of integrated circuit fabrication clear and accessible category of integrated circuit products and good equipment insight explanation etc can make general readers build up a clear overview about the whole integrated circuit industry This encyclopedia is designed as a reference book for scientists and engineers actively involved in integrated circuit research and development field In addition this book provides enough guide lines and knowledges to benefit enterprisers being interested in integrated circuit industry **Nanoelectronics** Joachim Knoch,2020-12-07 The author presents all aspects in theory and experiments of nanoelectronic devices starting from field effect transistors and leading to alternative device concepts such as Schottky barrier MOSFETs and band to band tunnel FETs Latest advances in Nanoelectronics as ultralow power nanoscale devices and the realization of silicon MOS spin qubits are discussed and finally a brief introduction into device simulations is given as well

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