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References

- [1] Newbury D E 1986 Electron beam–specimen interactions in the analytical electron microscope (Chapter 1 (1–26) in Joy D C et al Principles of analytical electron microscopy: New York:Springer) https://doi.org/10.1007/978-1-4899-2037-9_1
- [2] Joy D C 1995 Monte Carlo modeling for electron microscopy and microanalysis (New York: Oxford)
- [3] Reimer L and Lodding B 1984 Calculation and tabulation of Mott cross–sections for large–angle electron scattering *Scanning* 6 128–151 <https://doi.org/10.1002/sca.4950060303>
- [4] Czyzewski Z et al 1990 Calculations of Mott scattering cross section *Journal of Applied Physic.* 68 3066–3072 <https://doi.org/10.1063/1.346400>
- [5] Suzuki M et al 2018 Modeling of electron–specimen interaction in scanning electron microscope for e–beam metrology and inspection: challenges and perspectives *Proc. SPIE 10585, Metrology, Inspection, and Process Control for Microlithography XXXII*, pp.1058517 1–14 doi: [10.1117/12.2301383](https://doi.org/10.1117/12.2301383)
- [6] Murata K, Kyser D F and Ting C H 1981 Monte Carlo simulation of fast secondary electron production in electron beam resists *Journal of Applied Physics* 52 4396–4405 <https://doi.org/10.1063/1.329366>
- [7] Joy D C, Newbury D E and Myklebust R L 1982 The role of fast secondary electrons in degrading spatial resolution in the analytical electron microscope *Journal of Microscopy* 128 RP1–RP2 <https://doi.org/10.1111/j.1365-2818.1982.tb00442.x>
- [8] Bethe H A 1930 Zur Theorie des Durchgangs schneller Korpuskularstrahlen durch Materie. *Annalen der Physik* 5 325–400
- [9] Ferrell R A 1956 Angular dependence of the characteristic energy loss of electrons passing through metal foils *Physical Review* 101 554–563 <https://doi.org/10.1103/PhysRev.101.554>
- [10] Hirsch P B et al 1965 Electron microscopy of thin crystals (London: Butterworths)
- [11] Reimer L 1985 Scanning electron microscopy: physics of image formation and microanalysis (Berlin Heidelberg: Springer–Verlag)
- [12] Bongeler R et al 1993 Electron–specimen interactions in low–voltage scanning electron microscopy *SCANNING* 15 1–18 <https://doi.org/10.1002/sca.4950150102>
- [13] Niedrig H 1978 Physical background of electron backscattering *SCANNING* 1 17–34 <https://doi.org/10.1002/sca.4950010103>
- [14] Seiler H 1983 Secondary electron emission in the scanning electron microscope *Journal of Applied Physics* 54 R1–R18 <https://doi.org/10.1063/1.332840>
- [15] Joy D C and Joy C S 1996 Low voltage scanning electron microscopy *Micron* 27 247–263 [https://doi.org/10.1016/0968-4328\(96\)00023-6](https://doi.org/10.1016/0968-4328(96)00023-6)
- [16] Menzel E and Kubalek E 1979 Electron beam test system for VLSI circuit inspection *Proc. SEM Conference, edited by Johari O* Vol. I, pp. 297–304.

- [17] Fujioka H, Nakamae K and Ura K 1985 Signal-to-noise ratio in the stroboscopic scanning electron microscope *Journal of Physics E: Scientific Instruments* 18 598–603
- [18] Nakamae K, Fujioka H and Ura K 1981 Local field effects on voltage contrast in the scanning electron microscope *Journal of Physics D: Applied Physics* 14 1939–1960
- [19] Echlin P 2009 Handbook of Sample Preparation for Scanning Electron Microscopy and X-Ray Microanalysis (Springer) DOI: [10.1007/978-0-387-85731-2](https://doi.org/10.1007/978-0-387-85731-2)
- [20] Takemasa Y et al 2018 Advanced CD-SEM imaging methodology for EPE measurements *Proc. SPIE 10585, Metrology, Inspection, and Process Control for Microlithography XXXII*, pp.1058522 1–10 doi: [10.1117/12.2298393](https://doi.org/10.1117/12.2298393)
- [21] Kessel L van, Hagen C W and Kruit P 2019 Surface effects in simulations of scanning electron microscopy images *Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII*, pp.109590V 1–15 doi: [10.1117/12.2514824](https://doi.org/10.1117/12.2514824)
- [22] Arat K T, Klimpel T and Hagen C W 2019 Model improvements to simulate charging in scanning electron microscope *J. Micro/Nanolith. MEMS MOEMS* 18 044003 1–13 doi: [10.1117/1.JMM.18.4.044003](https://doi.org/10.1117/1.JMM.18.4.044003).
- [23] Lee C, Yokosuka T and Kazumi H 2018 Developing a flexible model of electron scattering in solid for charging analysis *Proc. SPIE 10585, Metrology, Inspection, and Process Control for Microlithography XXXII* pp.105852E 1–14 doi: [10.1117/12.2297371](https://doi.org/10.1117/12.2297371)
- [24] Goldstein J et al 1992. Scanning Electron Microscopy and X-ray Microanalysis (New York: Plenum Press) <https://doi.org/10.1007/978-1-4939-6676-9>
- [25] Zach J and Haider M 1995 Aberration correction in a low voltage SEM by a multipole corrector *Nuclear Instruments and Methods in Physics Research A* 363 316–325 [https://doi.org/10.1016/0168-9002\(95\)00056-9](https://doi.org/10.1016/0168-9002(95)00056-9)
- [26] Cheng Z H et al 2019 Application of aberration corrected low voltage SEM for metrology *Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII*, pp.1095922 1–9 doi: [10.1117/12.2516017](https://doi.org/10.1117/12.2516017)
- [27] ISO/TS 24597 2011 Microbeam analysis – scanning electron microscopy – methods of evaluating image sharpness, *ISO(the International Organization for Standardization)*
- [28] Diebold A C 2001 Silicon Semiconductor Metrology (in chapter 1, Handbook of Silicon Semiconductor Metrology (edited by Diebold A C, New York: Marcel Dekker Inc))
- [29] Wells O C 1974 Scanning Electron Microscopy (New York: McGraw-Hill Inc)
- [30] Nakagaki R, Honda T and Nakamae K 2009 Automatic recognition of defect areas on a semiconductor wafer using multiple scanning electron microscope images *Meas. Sci. Technol.* 20 pp.075503 1–12 <http://dx.doi.org/10.1088/0957-0233/20/7/075503>
- [31] Konvalina I et al 2019 In-Lens Band-Pass Filter for Secondary Electrons in Ultrahigh Resolution SEM *Materials* 12 pp.2307 1–13 <http://dx.doi.org/10.3390/ma12142307>
- [32] Suri A et al 2020 Analysis and detection of low-energy electrons in scanning electron microscopes using a Bessel box electron energy analyser *Journal of Electron Spectroscopy*

and Related Phenomena 241 pp.146823 1–8 <https://doi.org/10.1016/j.elspec.2019.02.002>

- [33] Niedrig H 1982 Electron backscattering from thin films *Journal of Applied Physics* 53 R15–R49 <https://doi.org/10.1063/1.331005>
- [34] Lin W R et al 2018 Fabrication and characterization of a high-performance multi-annular backscattered electron detector for desktop SEM *Sensors*, 18 pp.3093 1–13 <http://dx.doi.org/10.3390/s18093093>
- [35] Rau E I, Karaulov V Y and Zaitsev S V 2019 Backscattered electron detector for 3D microstructure visualization in scanning electron microscopy *Review of Scientific Instruments* 90 pp.023701 1–9 <https://doi.org/10.1063/1.5054746>
- [36] Radlička T, Unčovský M and Oral M 2018 In lens BSE detector with energy filtering *Ultramicroscopy* 189 102–108 <https://doi.org/10.1016/j.ultramic.2018.03.015>
- [37] Timischl F, Date M and Nemoto S 2012 A statistical model of signal-noise in scanning electron microscopy *SCANNING* 34 137–144 DOI 10.1002/sca.20282
- [38] Sakakibara M et al 2019 Impact of secondary electron emission noise in SEM *Microscopy* 68 279–288 doi: 10.1093/jmicro/dfz 009
- [39] Bunday B D 2020 Noise fidelity in SEM simulation *Proc. SPIE 11325, Metrology, Inspection, and Process Control for Microlithography XXXIV*, pp.113250R 1–9 doi: 10.1117/12.2559631
- [40] Lenthe W C 2018 Advanced detector signal acquisition and electron beam scanning for high resolution SEM imaging *Ultramicroscopy* 195 93–100 <https://doi.org/10.1016/j.ultramic.2018.08.025>
- [41] Papavieros G and Constantoudis V 2017 Line edge roughness measurement through SEM images: effects of image digitization and their mitigation *33rd European Mask and Lithography Conference* , pp. 104460K 1–11 doi: 10.1117/12.2294060
- [42] Roy V 2013 Spatial and transform domain filtering method for image de-noising: a review *I.J. Modern Education and Computer Science* 5 41–49 DOI: 10.5815/ijmecs.2013.07.05
- [43] Mack C A, Roey F V and Lorusso G F 2019 Unbiased roughness measurements: subtracting out SEM effects, part 3 *Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII* pp.109590P 1–10 doi: 10.1117/12.2515898
- [44] Mack C A and Bunday B D 2016 Improvements to the analytical linescan model for SEM metrology *Metrology, Proc. SPIE 9778, Inspection, and Process Control for Microlithography XXX* pp.97780A 1–9 <https://doi.org/10.1117/12.2218443>
- [45] Giannatou E et al 2019 Deep learning nanometrology of line edge roughness *Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII* pp.1095920 1–11 doi: 10.1117/12.2520941
- [46] Zhang K et al 2017 Beyond a gaussian denoiser: residual learning of deep CNN for image denoising *IEEE Transactions on Image Processing* 26 3142–3155 DOI: 10.1109/TIP.2017.2662206
- [47] Midoh Y and Nakamae K 2019 Image quality enhancement of a CD-SEM image using

- conditional generative adversarial networks *Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII* pp.109590B 1–10 doi: [10.1117/12.2515152](https://doi.org/10.1117/12.2515152)
- [48] Isola P et al 2017 Image-to-image translation with conditional adversarial networks *2017 IEEE Conference on Computer Vision and Pattern Recognition* pp.5967–5976 DOI: [10.1109/CVPR.2017.632](https://doi.org/10.1109/CVPR.2017.632)
- [49] Yu L et al 2020 SEM image quality enhancement: an unsupervised deep learning approach *Proc. SPIE 11325, Metrology, Inspection, and Process Control for Microlithography XXXIV* pp.1132527 1–9 doi: [10.1117/12.2552883](https://doi.org/10.1117/12.2552883)
- [50] Lehtinen J et al 2018 Noise2Noise: Learning image restoration without clean data PMLR 80 pp.2965–2974
- [51] Iida S et al 2016 Investigation of defect detectability for extreme ultraviolet patterned mask using two types of high-throughput electron-beam inspection systems *J. Micro/Nanolith. MEMS MOEMS* 15, pp.013510 1–7 doi: [10.1117/1.JMM.15.1.013510](https://doi.org/10.1117/1.JMM.15.1.013510)
- [52] Ma E 2018 Multiple beam technology development and application for defect inspection on EUV wafer/mask *Proc. SPIE 10810, Photomask Technology 2018* pp.1081014 1–9 doi: [10.1117/12.2503857](https://doi.org/10.1117/12.2503857)
- [53] Liang T et al 2020 EUV mask infrastructure and actinic pattern mask inspection *Proc. SPIE 11323, Extreme Ultraviolet (EUV) Lithography XI* pp.1132310 1–13 doi: [10.1117/12.2554496](https://doi.org/10.1117/12.2554496)
- [54] Nakagaki R, Takagi Y and Nakamae K 2010 Automatic recognition of circuit patterns on semiconductor wafers from multiple scanning electron microscope images *Measurement Science and Technology* 21 pp.085501 1–14 <http://dx.doi.org/10.1088/0957-0233/21/8/085501>
- [55] Harada M, Obara K and Nakamae K 2017 A robust SEM auto-focus algorithm using multiple band-pass filters *Measurement Science and Technology* 28 pp.015403 1–10 <http://dx.doi.org/10.1088/1361-6501/28/1/015403>
- [56] Harada M, Minekawa Y and Nakamae K 2019 Defect detection techniques robust to process variation in semiconductor inspection *Measurement Science and Technology* 30 pp.035402 1–10 <https://doi.org/10.1088/1361-6501/aafd77>
- [57] Ouchi M et al A trainable die-to-database for fast e-Beam inspection: learning normal images to detect defects *Proc. SPIE 11325, Metrology, Inspection, and Process Control for Microlithography XXXIV* pp.113252F 1–9 doi: [10.1117/12.2551456](https://doi.org/10.1117/12.2551456)
- [58] Chawla N V et al 2002 SMOTE: Synthetic Minority Oversampling Technique *Journal of Artificial Intelligence Research* 16 321–357 DOI: <https://doi.org/10.1613/jair.953>
- [59] Lee P et al 2020 Automated semiconductor wafer defect classification dealing with imbalanced data *Proc. SPIE 11325, Metrology, Inspection, and Process Control for Microlithography XXXIV* pp.1132526 1–7 doi: [10.1117/12.2552838](https://doi.org/10.1117/12.2552838)
- [60] Fukuda H et al 2018 Measurement of pattern roughness and local size variation using CD-SEM *J. Micro/Nanolith. MEMS MOEMS* 17 pp.041004 1–9 doi: [10.1117/1.JMM.17.4.041004](https://doi.org/10.1117/1.JMM.17.4.041004).

- [61] Zhiqiang W et al 2019 What is prevalent CD-SEM's role in EUV era? *Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII* pp.1095914 1–10 doi: [10.1117/12.2514697](https://doi.org/10.1117/12.2514697)
- [62] Bizen D et al 2019 CD metrology for EUV resist using high-voltage CD-SEM: shrinkage, image sharpness, repeatability, and line edge roughness *J. Micro/Nanolith. MEMS MOEMS* 18 pp.034004 1–6 doi: [10.1117/1.JMM.18.3.034004](https://doi.org/10.1117/1.JMM.18.3.034004).
- [63] Pu L et al 2019 Analyze line roughness sources using power spectral density (PSD) *Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII* pp.109592W 1–8 doi:[10.1117/12.2516570](https://doi.org/10.1117/12.2516570)
- [64] Kessel L, Huisman T and Hagen C W 2020 Understanding the influence of 3D sidewall roughness on observed line-edge roughness in scanning electron microscopy images *Proc. SPIE 11325, Metrology, Inspection, and Process Control for Microlithography XXXIV* pp.113250Z 1–16 <https://doi.org/10.1117/12.2550240>
- [65] Han J H 2018 Advanced technique for ultra-thin residue inspection with sub-10nm thickness using high-energy back-scattered electrons *Proc. SPIE 10585, Metrology, Inspection, and Process Control for Microlithography XXXII* pp.1058521 1–6 doi: [10.1117/12.2296982](https://doi.org/10.1117/12.2296982)
- [66] Nishihata T et al 2019 Depth measurement technique for extremely deep holes using back-scattered electron images with high voltage CD-SEM *Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII* pp.109591B 1–9 doi: [10.1117/12.2514799](https://doi.org/10.1117/12.2514799)
- [67] Sun W et al 2019 High voltage CD-SEM based metrology for 3D-profile measurement using depth-correlated BSE signal *Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII* pp.1095915 1–8 doi: [10.1117/12.2511272](https://doi.org/10.1117/12.2511272)
- [68] Tu L et al 2020 3D-NAND wafer process monitoring using high voltage SEM with auto e-beam tilt technology *Proc. SPIE 11325, Metrology, Inspection, and Process Control for Microlithography XXXIV* pp.113250L 1–8 doi: [10.1117/12.2551610](https://doi.org/10.1117/12.2551610)
- [69] Sun W et al 2020 Accuracy improvement of 3D-profiling for HAR features using deep learning *Proc. SPIE 11325, Metrology, Inspection, and Process Control for Microlithography XXXIV* pp.113250N 1–8 doi: [10.1117/12.2551458](https://doi.org/10.1117/12.2551458)
- [70] Taftia A P et al Recent advances in 3D SEM surface reconstruction *Micron* 78 54–66. <http://dx.doi.org/10.1016/j.micron.2015.07.005>
- [71] Villarrubia J S Tondare V N and Vladar A E 2016 Virtual rough samples to test 3D nanometer-scale scanning electron microscopy stereo photogrammetry *Proc. SPIE 9778, Metrology, Inspection, and Process Control for Microlithography XXX*; pp.1–19 doi:[10.1117/12.2219777](https://doi.org/10.1117/12.2219777).
- [72] Valade C et al 2019 Tilted beam scanning electron microscopy, 3-D metrology for microelectronics industry *J. Micro/Nanolith. MEMS MOEMS* 18 pp.034001 1–13 doi: [10.1117/1.JMM.18.3.034001](https://doi.org/10.1117/1.JMM.18.3.034001).
- [73] Neumann J T et al 3D analysis of high-aspect ratio features in 3D-NAND *Proc. SPIE 11325, Metrology, Inspection, and Process Control for Microlithography XXXIV* pp.113250M 1–11 doi: [10.1117/12.2551610](https://doi.org/10.1117/12.2551610)

10.1117/12.2552006

- [74] Overlay control *Wikipedia* https://en.wikipedia.org/wiki/Overlay_control
- [75] Inoue O and Hasumi K 2019 Review of scanning electron microscope-based overlay measurement beyond 3-nm node device *J. Micro/Nanolith. MEMS MOEMS* 18 pp.021206 1–15 doi: 10.1117/1.JMM.18.2.021206.
- [76] Abramovitz Y et al 2020 Accelerating on-device overlay metrology accuracy verification *Proc. SPIE 11325, Metrology, Inspection, and Process Control for Microlithography XXXIV*, pp.1132515 1–7 doi: 10.1117/12.2568682
- [77] Babu M R et al 2020 Foundry approach for layout risk assessment through comprehensive pattern harvesting and large-scale data analysis *Proc. SPIE 11328, Design-Process-Technology Co-optimization for Manufacturability XIV* pp.113280H 1–9 doi: 10.1117/12.2551939
- [78] Ura K 1981 Address error of electron beam by local electric field *Optik* 58 281–284
- [79] Nakamae K, Fujioka H and Ura K Measurements of deep penetration of low-energy electrons into metal-oxide-semiconductor structure *Journal of Applied Physics* 52, 1306–1308 <https://doi.org/10.1063/1.329756>