| Title | Electron microscopy in semiconductor inspection |
|---|---|
| Author(s) | Nakamae, Koji |
| Citation | Measurement Science and Technology. 2021, 32(5), p. 052003 |
| Version Type | AM |
| URL | https://hdl.handle.net/11094/79128 |
| rights | © 2021 IOP Publishing Ltd. This Accepted Manuscript is available for reuse under a CC BY-NC-ND licence. |
| Note | |

# 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

[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

[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

[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

[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

[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.

[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

[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

[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

[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

[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

[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

[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

[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

[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

[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

[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

[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.

[61] Zhigang 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

[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.

[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

[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

[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

[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

[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

[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

[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.

[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.

[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:

10.1117/12.2552006

[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