REFERENCES

[1] H. Uetsuka, “AWG Techologies for Dense WDM Applications”, *IEEE J. Select. Topics Quantum Electron.*, vol. 10, pp.393-402, March/April 2004.

[2] J. P. Laude, *DWDM Fundamentals, Components, and Applications*, Artech House, Norwood, MA, 2002.

[3] B.H. Robinson and L.R. Dalton, “Monte Carlo Statistical Mechanical Simulations of the Competition of Intermolecular Electrostatic and Poling-Field Interactions in Defining Macroscopic Electro-Optic Activity for Organic Chromophore/Polymer Materials,” *J. Phys.Chem. A*, vol. 104, pp. 4785-4795, Apr. 2000.

[4] Saleh and Teich, *Fundamentals of Photonics*, Wiley InterScience.

[5] G.T. Paloczi, Y. Huang and A. Yariv, “Free-Standing All-Polymer Microring Resonator Optical Filter,” *Electron. Lett.*, vol. 39, pp. 1-3, Nov. 2003.

[6] D. Chen, H. R. Fetterman, A. Chen, W. H. Steier, L. R. Dalton, W. Wang, and Y. Shi, “Demonstration of 110GHz, Electro-optic Polymer Modulators,” *Appl. Phys. Lett.*, vol. 70, pp. 3335-3337, June 1997.

[7] Y. Shi, C. Zhang, H. Zhang, J.H. Bechtel, L.R. Dalton, B.H. Robinson, and W.H. Steier, “Low (sub–1-volt) Halfwave Voltage Polymeric Electro-Optic Modulators Achieved by Controlling Chromophore Shape,” *Science*, vol. 288, pp. 119-122, April 2000.

[8] S.L. Chuang, *Physics of Optoelectronic Devices*, John Wiley & Sons, Inc., New York, New York, 1995.

[9] R.C. Twu, C.Y. Chang, and W.S. Wang, “A Zn-diffused Mach-Zehnder Modulator on Lithium Niobate at 1.55μm Wavelength,” *Microwave Optical Technol. Lett.*, vol. 43, pp. 142-144, March 2004.

[10] F. Lucchi, D. Janner, M. Belmonte, S. Balsamo, M. Villa, S. Giurgola, P. Vergani and V. Pruneri, “Very Low Voltage Single Drive Domain Inverted $LiNbO_3$ Integrated Electro-optic Modulator,” *Optics Express*, vol. 15, pp.10739-10743, Aug. 2007.

[11] R.A. Soref and B.R. Bennett, “Electrooptical Effects in Silicon,” *IEEE J. Quantum Electron.*, vol. QE-23, pp. 123-129, Jan. 1987.

[12] A. Liu. R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu, and M. Paniccla, “A high-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor,” *Nature*, vol. 427, pp. 615-618, Feb. 2004.

[13] F.Y. Gardes, G.T. Reed, N.G. Emerson and C.E. Png, “A Sub-Micron Depletion-type Photonic Modulator in Silicon On Insulator,” *Optics Express*, vol. 13, pp. 8845-8854, Oct. 2005.

[14] A. Liu, L. Liao, D. Rubin, H. Nguyen, B. Ciftcioglu, Y. Chetrit, N. Izhaky, and M. Paniccla, “High-speed optical modulation based on carrier depletion in a silicon waveguide,” *Optics Express*, vol. 15, pp. 660-668, Jan. 2007.

[15] F. Gan and F.X. Kartner, “High-Speed Silicon Electrooptic Modulator Design,” *IEEE Photon. Technol. Lett.*, vol. 17, pp. 1007-1009, May 2005.

[16] T.D. Kim, J. Luo, Y.J. Cheng, Z. Shi, S. Hau, S.H. Jang, X.Y. Zhou, Y. Tian, B. Polishak, S. Huang, H. Ma, L.R. Dalton, A.K.Y. Jen, "Binary Chromophore Systmes in Nonlinear Optical Dendrimers and Polymers for Large Electroptic Activities,” *J. Phys. Chem. C*, vol. 112, pp. 8091-8098, April 2008.

[17] R.J. Michalak, Y.H. Kuo, F.D. Nash, A. Szep, J.R. Carrey, P.M. Payson, F. Haas, B.F. McKeon, P.R. Cook, G.A. Brost, J. Luo, A.K.Y. Jen, L.R. Dalton, W.H. Steier, “High-Speed AJL8/APC Polymer Modulator,” *IEEE Photon. Technol. Lett.*, vol. 18, pp. 1207-1209, June 2006.

[18] M. Lee, H.E. Katz, C. Erben, D.M. Gill, P. Gopalan, J.D. Heber, D.J. McGee, “Broadband Modulation of Light by Using an Electro-Optic Polymer,” *Science*, vol. 298, pp.1401-1403, Nov. 2002.

[19] I. Faderl, P. Labeye, P. Gidon, and P. Mottier, “Integration of an Electrooptic Polymer in an Integrated Silicon Optics Circuit on Silicon,” *J. Lightwave Technol.*, vol. 13, pp. 2020-2026, Oct. 1995.

[20] M. Hochberg, T. Baehr-Jones, G. Wang, M. Shearn, K. Harvard, J. Luo, B. Chen, Z. Shi, R. Lawson, P. Sullivan, A.K.Y. Jen, L. Dalton, and A. Scherer, “Terahertz All-optical Modulation in a Silicon-Polymer Hybrid System,” *Nature Materials*, vol. 5, pp. 703-709, Sept. 2006.

[21] M. Hochberg, T. Baehr-Jones, G. Wang, J. Huang, P. Sullivan, L. Dalton, and A. Scherer, “Towards a Millivolt Optical Modulator with Nano-Slot Waveguides,” *Optics Express*, vol. 15, pp. 8401-8410, June 2007.

[22] K. Kleven-McLauchlan and S.T. Dunham, “Analysis of a Compact Modulator Incorporating a Hybrid Silicon/Electro-Optic Polymer Waveguide,” *J. Select Topics Quantum Electron.*, vol. 12, pp. 1455-1460, Nov./Dec. 2006.

[23] C. A. Barrios, V. R. Almeida, R. R. Panepucci, B. S. Schmidt, and M. Lipson, "Compact silicon tunable Fabry-Perot resonator with low power consumption," *IEEE Photon. Technol. Lett.*, vol. 16, pp. 506-508, Feb. 2004.

[24] B. Schmidt, Q. Xu, J. Shakya, S. Manipatruni, and M. Lipson, "Compact Electro-optic Modulator on Silicon-on-Insulator Substrates Using Cavities with Ultra-Small Modal Volumes," *Optics Express*, vol.15, pp. 3140-3146, March 2007.

[25] H. Gan, H. Zhang, C.T. DeRose, R.A. Norwood, M. Fallahi, J. Luo, A.K.Y. Jen, B. Liu, S.T. Ho, and N. Peyghambarian, "Optical Modulation From an Electro-optic Polymer Based Hybrid Fabry-Perot Etalon Using Transparent Conducting Oxides," *Proc. SPIE*, vol. 6470, pp. 64700F-1 – 64700F-8, Jan. 2007.

[26] J. Niehusmann, A. Vorckel, P.H. Bolivar, T. Wahlbrink, W. Henschel, H. Kurz, "Ultrahigh-Quality-Factor Silicon-on-Insulator Microring Resonator," *Optics Lett.*, vol. 29, pp. 2861-2863, Dec. 2004.

[27] B. Miao, P. Yao, J. Murakowski, and D.W. Prather, "Fabrication of Silicon Microring Resonators with Narrow Coupling Gaps," *J. Microlith., Microfab., Microsys.*, vol. 4, pp.23013-1 - 23013-5, Apr. 2005.

[28] R. Grover, T.A. Ibrahim, T.N. Ding, Y. Leng, L.C. Kuo, S. Kanakaraju, K. Amarnath, L.C. Calhoun, and P.T. Ho, "Laterally Coupled InP-Based Single Mode Microractrack Notch Filter," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 1082-1084, Aug. 2003.

[29] B.G. Lee, B.A. Small, K. Bergman, Q. Xu and M. Lipson, "Transmission of High-Data-Rate Optical Signals Through a Micrometer-Scale Silicon Ring Resonantor," *Optics Lett.*, vol. 31, pp. 2701-2703, Sept. 2006.

[30] P. Rabiei, W.H. Steier, C. Zhang, and L.R. Dalton, "Polymer Micro-Ring Filters and Modulators," *J. Lightwave Technol.*, vol. 20, pp. 1968-1975, Nov. 2002.

[31] H. Tazawa, Y.H. Kuo, I. Dunayevskiy, J. Luo, A.K.Y. Jen, H.R. Fetterman, and W.H. Steier, "Ring Resonator-Based Electrooptic Polymer Traveling-Wave Modulator," *J. Lightwave Technol.*, vol. 24, pp. 3514-3518, Sept. 2006.

[32] T. Baehr-Jones, M. Hochberg, G. Wang, R. Lawson, Y. Liao, P. Sullivan, L. Dalton, A. Jen, and A. Scherer, "Optical modulation and detection in slotted silicon waveguides," *Optics Express,* vol. 13, pp. 5216-5226, July 2005.

[33] V. R. Almeida, Q. Xu, C. A. Barrios, and M. Lipson, "Guiding and confining light in void nanostructures," *Optics Lett.* vol. 29, pp. 1209-1211, June 2004.

[34] J. S. Foresi, P. R. Villeneuve, J. Ferrera, E. R. Thoen, G. Steinmeyer, S. Fan, J. D. Joannopoulos, L. C. Kimerling, H. I. Smith, and E. P. Ippen, "Photonic-bandgap Microcavities in Optical Waveguides," *Nature*, vol. 390, pp. 143-145, Nov. 1997.

[35] R.G. Hunsperger, *Integrated Optics: Theory and Technology*, Springer, Berlin, Germany, 2002.

[36] E.D. Palick, Ed., *Handbook of Optical Constants of Solids*, Elsevier, 1998.

[37] M.C. Oh, H. Zhang, C. Zhang, H. Erlig, Y. Chang, B. Tsap, D. Chang, A. Szep, W.H. Steier, H.R. Fetterman, and L.R. Dalton, "Recent Advances in Electroopic Polymer Modulators Incorporating Highly Nonlinear Chromophore," *J. Select. Topics Quantum Electron.*, vol. 7, pp. 826-835, Sept. 2001.

[38] L. Dalton, B. Robinson, A. Jen, P. Ried, B. Eichinger, P. Sullivan, A. Akelaitis, D. Bale, M. Haller, J. Luo, S. Liu, Y. Liao, K. Firestone, N. Bhatambrekar, S. Bhattacharjee, J. Sinness, S. Hammond, N. Buker, R. Snoeberger, M. Lingwood, H. Rommel, J. Amend, S.H. Jang, A. Chen and W. Steier, "Electro-optic Coefficients of 500pm/V and Beyond for Organic Materials," *Proc. SPIE*, vol. 5935, pp. 593502-1 – 593502-12, 2005.

[39] H. Kang, A. Facchetti, P. Zhu, H. Jiang, Y. Yang, E. Cariati, S. Righetto, R. Ugo, C. Zuccaccia, A. Macchioni, C.L. Stern, Z. Liu, S.T. Ho and T.J. Marks, "Exceptional Molecular Hyperpolarizabilities in Twisted π-Electron System Chromophores," *Angew. Chem. Int. Ed.*, vol. 44, pp.7922-7925, 2005.

[40] D. M. Kearns and R. W. Beatty, *Basic Theory of Waveguide Junctions and Introductory Microwave Network Analysis*, Pergamon Press, Oxford, London, 1967.

[41] *FEMLAB 3.1 Electromagnetic Module User's Guide*, Comsol AB, Stockholm, Sweden, Oct. 2004.

[42] Ansoft HFSS v11, ANSYS Inc., www.ansoft.com.

[43] P.E. Lewis and J.P. Ward, *The Finite Element Method*, Addison-Wesley Publishing Co., Wokingham, England, 1991.

[44] R. Syms and J. Cozens, *Optical Guided Waves and Devices,* McGraw-Hill Book Co., London, England, 1992.

[45] G. Xu, J. Ma, S.T. Ho and T.J. Marks, "Low-Voltage Electro-Optic Modulator Structure Using Transparent Conducting Oxide with High Conductivity-Loss Ratio as Electrodes," *Proc. SPIE*, vol. 5935, pp. 0Y1-0Y9, Sept. 2005.

[46] M. Lipson, “Compact Electro-Optic Modulators on a Silicon Chip,” *IEEE J. Select Topic Quantum Electron.*, vol. 12, pp. 1520-1526.

[47] P. Bhattacharya, *Semiconductor Optoelectronic Devices*, Prentice-Hall Inc., Upper Saddle River, NJ, 1997.

[48] H. Statz, G.A. DeMars, L. Davis, and A. Adams, “Surface States on Silicon and Germanium Surfaces,” *Phys. Rev.*, vol. 101, pp. 1272-1281, Feb. 1956.

[49] R.S. Muller and T.I. Kamins, *Device Electronics for Integrated Circuits, 3rd Ed.*, John Wiley and Sons, New York, New York, 2003.

[50] Y. Taur and T. H. Ning, *Fundamentals of Modern VSLI Devices*, Cambridge University Press, New York, New York, 2002.

[51] P.D. Hewitt and G.T. Reed, “Improving the Response of Optical Phase Modulators in SOI by Computer Simulation,” *J. Lightwave Technol.*, vol. 18, pp. 443-450, March 2000.

[52] J.M. Lee, D.J. Kim, H. Ahn, S.H. Park and G. Kim, “Temperature Dependence of Silicon Nanophotonic Ring Resonator With a Polymeric Overlayer,” *J. Lightwave Technol.*, vol. 25, pp. 2236-2243, Aug. 2007.

[53] F. Payne and J. Lacey, “A theoretical analysis of scattering loss from planar optical waveguides,” *Optical and Quantum Electron.,* vol. 26, pp. 977-986, Nov. 1994.

[54] IBM Photonics Research, domino.research.ibm.com/comm/research_projects.nsf/pages/photonics.fabrication.html

[55] R. Legtenberg, H. Jansen, M. deBoer, and M. Elwenspoek, “Anisotropic reactive ion etching of silicon using $SF_6/O_2/CHF_3$ gas mixtures,” *J. Electrochem. Soc.*, vol. 142, pp. 2020-2028, June 1995.

[56] K. Lee, D. Lim, L. Kimerling, J. Shin, and F. Cerrina, “Fabrication of ultralow-loss Si/SiO_2 waveguides by roughness reduction,” *Optics Lett.*, vol. 26, pp. 1888-1890, Dec. 2001.

[57] D. Sparacin, S. Spector, and L. Kimerling, “Silicon waveguide sidewall smoothing by wet chemical oxidation,” *J. Lightwave Technol.,* vol. 23, pp. 2455-2461, August 2005.

[58] J. D. Plummer, M. D. Deal, P. B. Griffin, *Silicon VLSI Techology: Fundamentals, Practice, and Modeling*, Prentice-Hall Publishing, Upper Saddle River, New Jersey, 2000.

[59] J. F. Gibbons, W. S. Johnson, and S. W. Mylroie, *Projected Range Statistics: Semiconductors and Related Materials, 2nd Edition*, Dowden, Hutchinson, and Ross Inc., Stroudsburg, Pennsylvania, 1975.

[60] Sentaurus Process, *Synopsys, Inc.*, www.synopsys.com

[61] D.D. Perovic, M.R. Castell, A. Howie, C. Lavoie, T. Tiedje, and J.S.W. Cole, "Field-emission SEM Imaging of Compositional and Doping Layer Semiconductor Superlattices," *Ultramicroscopy*, vol. 58, pp. 104-113, 1995.

[62] G. Piaszenski, U. Barth, A. Rudzinski, A. Rampe, A. Fuchs, M. Bender, and U. Plachetka, "3D Structures for -NIL Template Fabrication with Grayscale E-beam Lithography," *Microelectronic Engineering*, vol. 84, pp. 945-948, Jan. 2007.

[63] K. R. Williams, K. Gupta and M. Wasilik, "Etch Rates for Micromachining Processing – Part II", *IEEE J. Microelectromechanical Sys.*, vol. 12, pp. 761-778, Dec. 2003.

[64] B.G. Lee, B.A. Small, K. Bergman, Q. Xu and M. Lipson, "Transmission of High-Data-Rate Optical Signals Through a Micrometer-Scale Silicon Ring Resonantor," *Optics Lett.*, vol. 31, pp. 2701-2703, Sept. 2006.

[65] H. Tazawa, Y.H. Kuo, I. Dunayevskiy, J. Luo, A.K.Y. Jen, H.R. Fetterman, and W.H. Steier, "Ring Resonator-Based Electrooptic Polymer Traveling-Wave Modulator," *J. Lightwave Technol.*, vol. 24, pp. 3514-3518, Sept. 2006.

[66] E.J. Klein, D.H. Geuzebroek, H. Kelderman, and A. Driessen, "Wavelength-Selective Switch Using Thermally Tunable Microring Resonators," MM1, 2003.

[67] M.K. Chin and S.T. Ho, "Design and Modeling of Waveguide-Coupled Single-Mode Microring Resonators," *J. Lightwave Technol.*, vol. 16, pp. 1433-1446, Aug. 1998.

[68] L. Lewin, D.C. Chang, and E.F. Kuester, *Electromagnetic Waves and Curved Structures*, Peter Peregrinus Ltd., Stevenage, England, 1977.

[69] M. Oxborrow, "Traceable 2D Finite-Element Simulation of the Whispering Gallery Modes of Axisymmetric Electromagnetic Resonators," *Unpublished*, March 2007.

[70] V. Van, P.P. Absil, J.V. Hyrniewicz, and P.T. Ho, "Propagation Loss in Single-Mode GaAs-AlGaAs Microring Resonators: Measurement and Model," *J. Lightwave Technol.*, vol. 19, pp. 1734-1739, Nov. 2001.

[71] B.E. Little, S.T. Chu, H.A. Haus, J. Foresi, and J.P. Laine, "Microring Resonator Channel Dropping Filters," *J. Lightwave Technol.*, vol. 15, pp. 998-1005, June 1997.

[72] R.C. Hall, R. Mittra and K.M. Mitzner, "Analysis of Multilayered Periodic Structures Using Generalized Scattering Matrix Theory," *IEEE Trans. Antenna Prop.*, vol. 36, pp. 511-517, April 1988.

[73] Q.Y. Lu, W.H. Guo, R. Phelan, D. Byrne, J.F. Donegan, P. Lambkin, and B. Corbett, "Analysis of Slot Characteristics in Slotted Single-Mode Semiconductor Lasers Using the 2D Scattering Matrix Method," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 2605-2607, Dec. 2006.

[74] H.W. Glock, K. Rothemund, and U. vanRienen, "CSC – A procedure for coupled s-parameter calculations," *IEEE Trans. Magnetics*, vol. 38, pp. 1173-1176, March 2002.

[75] S. Xiao, M.H. Khan, H. Shen, and M. Qi, "Compact Silicon Microring Resonators with Ultra-Low Propagation Loss in the C Band," *Optics Express*, vol. 15, pp. 14467-14475, Oct. 2007.

[76] W. Chen, Z. Wang, W. Chen, and Y. J. Chen, "General Ring-Resonator Analysis and Characterization by Characteristic Matrix," *IEEE J. Lightwave Technol.*, vol. 23, pp.915-922, Feb. 2005.

[77] F. Xia, L. Sekaric, M.O'Boyle, and Y. Vlasov, "Coupled Resonator Optical Waveguides Based on Silicon-on-Insulator Photonic Wires," *Appl. Phys. Lett.*, vol. 89, pp. 041122-01- 041122-03, July 2006.

[78] D. Marcuse, *Theory of Dielectric Optical Waveguides*, Academic Press Inc., San Diego, CA, 1991.

[79] F. Xia, L. Sekaric, and Y.A. Vlasov, "Mode Conversion Losses in Silicon-on-Insulator Photonic Wire Based Racetrack Resonators," *Optics Express*, vol. 14, pp. 3872-3886, May 2006.

APPENDIX A – PROCESS VARIATIONS FOR GRAY-SCALE EBL

Variations of the process steps for gray-scale lithography for EBL exposure of PMMA and pattern transfer into silicon.

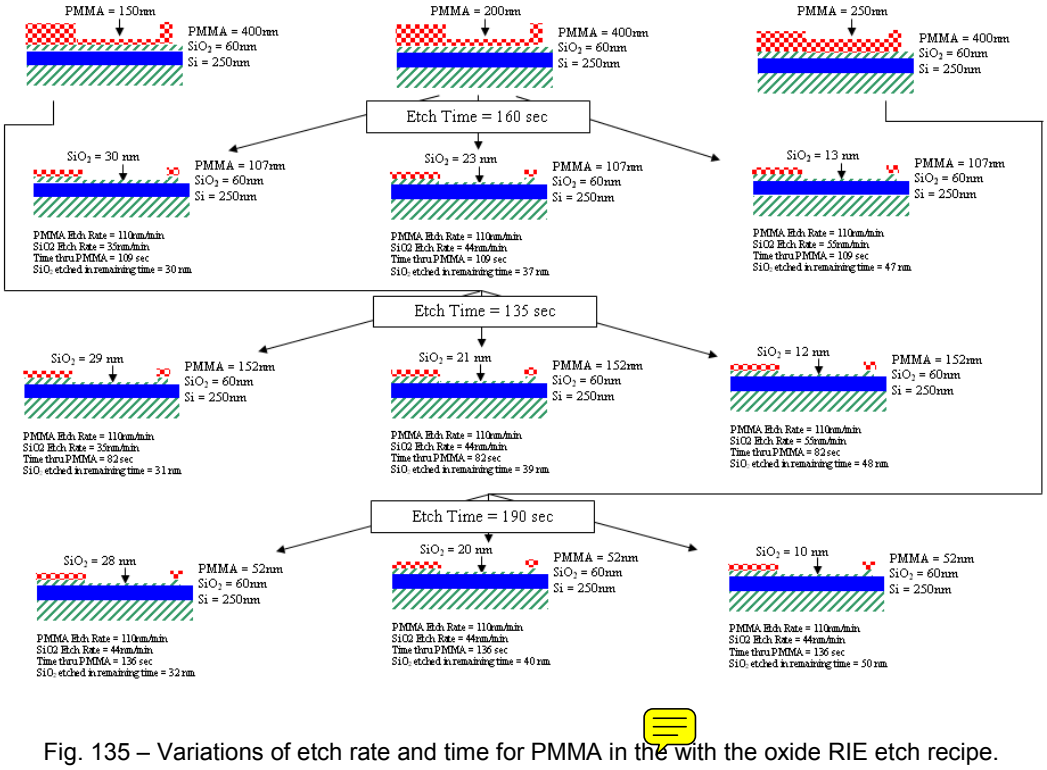

Fig. 135 – Variations of etch rate and time for PMMA in the with the oxide RIE etch recipe.

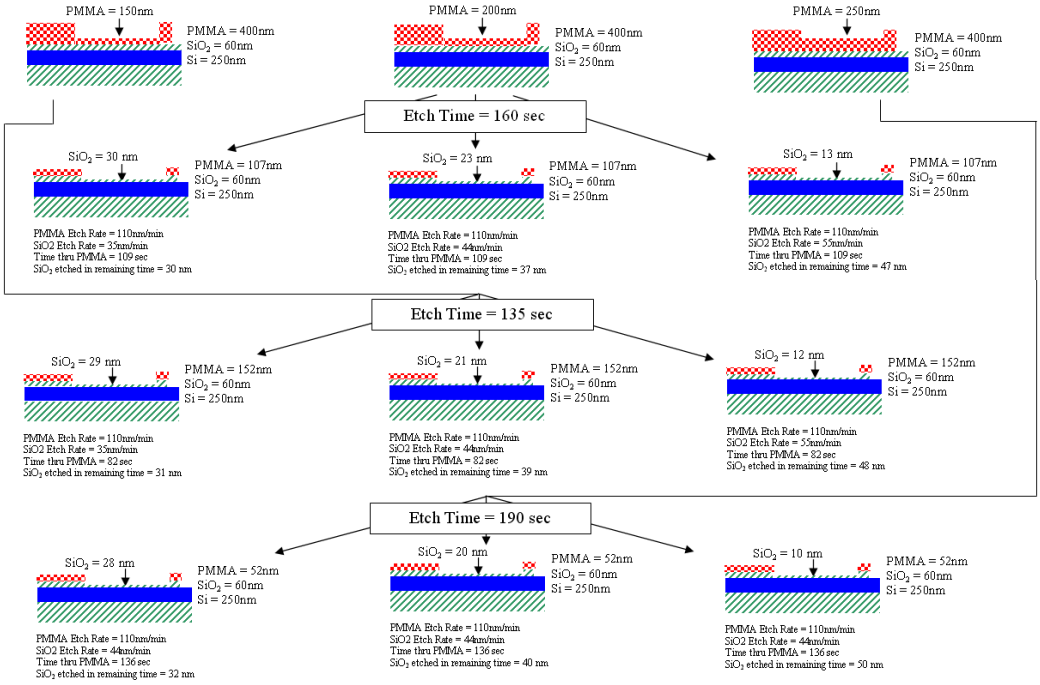

Fig. 136 – Process flow for variations of etch rate and time of silicon, silicon dioxide and PMMA for grayscale lithography.

APPENDIX B – PROCESS RECIPES

The recipes used for the process development at the Washington Technology Center are provided below.

1. Silicon sidewall smoothing process [57]
    a. SC1 Dip
        i. Wet bath mixture of 5 H_2O: 1 H_2O_2: 1 NH_4OH
        ii. Time: 10min
        iii. Temperature: 80°C
    b. DI Water Rinse
    c. HF Dip
        i. Wet bath mixture of 1 HF: 50 H_2O
        ii. Time: 15sec
        iii. Temperature: 25°C
    d. DI Water Rinse
    e. SC2 Dip
        i. Wet bath mixture of 6 H_2O: 1 H_2O_2: 1 HCl
        ii. Time: 15min
        iii. Temperature: 80°C
    f. DI Water Rinse
    g. Repeat five times

2. Spin coating AZ1512 to a 1.2μm thickness
    a. Dispense photoresist at room temperature
    b. Spin with the following speeds:
        i. Velocity 1 – 500rpm
        ii. Ramp 1 – 250rpm
        iii. Time 1 – 10sec
        iv. Velocity 2 – 3000rpm
        v. Ramp 2 – 1500rpm
        vi. Time 2 – 20sec
        vii. Ramp down to stop
    c. Prebake at 90° for 30min for a soft bake before exposure

3. Developing Recipe for AZ15121
    a. AZ351 Dip
        i. Wet bath mixture of 4 H_2O: 1 AZ351
        ii. Time: 60sec for a 1.2μm photoresist thickness
        iii. Temperature: 80°C
    b. Rinse with DI water
    c. Spin dry to remove excess water
    d. Postbake at 110°C for 30min

4. Photoresist removal
    a. If dry processing steps have been performed: reactive ion etch with O_2
        i. Pressure: 100mT
        ii. Power: 150W
        iii. O_2 flow: 100sccm
        iv. Time: 60sec
    b. EKC830 Dip
        i. Temperature: 75°C
        ii. Time: 10min
    c. AZ300T Dip
        i. Temperature: 90°C
        ii. Time: 5min
    d. DI water rinse
    e. Spin dry

5. Spin Coat Recipe for PMMA
    a. Dispense resist directly onto wafer
    b. Spin with recipe:
        i. Velocity 1: 500rpm
        ii. Ramp 1: 500rpm

iii. Time 1: 10sec

iv. Velocity 2: 5000rpm

v. Ramp 2: 500rpm

vi. Time 2: 45sec

vii. Ramp down to stop

c. Prebake at 180°C for 90sec

6. PMMA Developing Recipe

a. Develop PMMA with MIBK

i. Wet solution mixture of 1 MIBK: 3 IPA

ii. Temperature: 25°C

iii. Time 70sec

b. Rinse with IPA

c. Dry with N_2

d. Postbake in convection oven

i. Temperature: 90°C

ii. Time: 30min

VITA

Kjersti Kleven is interested in integrated optics and optical device design, especially focusing on CMOS-compatible platforms. Her current research is focused on the analysis of hybrid silicon/electro-optic polymer resonant cavity devices and approaches for reducing the computational expense of modeling these structures. She completed her Bachelor of Science degree in Electrical Engineering at Embry-Riddle Aeronautical University in Prescott, AZ in 2003 and a Master of Science degree in Electrical Engineering at the University of Washington in Seattle, WA in 2005. She earned her Doctor of Philosophy in Electrical Engineering in 2008 also at the University of Washington.