

Index

a

activation energy, for adsorption 12
 adsorption
 activation energy for 12
 of chemically active species 7
 dissociative 12, 14
 process 11, 163
 advanced CCP reactors 252
 advanced logic metal gate structures 88
 afterglow 260–262, 265
 ammonium hexafluorosilicate 47, 87
 angular dependence 20, 31, 139, 140,
 198, 227
 angular distributions, neutral beams 30
 area selective deposition 75–77
 Arrhenius equation 12, 13, 30
 aspect ratio dependent etching (ARDE)
 3, 10, 97
 atomic layer etching 191
 of HfO_2 110
 of SiO_2 110
 atomic layer etching (ALE) 3, 4, 36, 37
 application examples 123
 conversion ALE 58
 ligand exchange ALE 55
 oxidation/fluorination ALE process
 60
 performance metrics 110–123
 synergy requirement for 91
 with directional removal step and
 modification by chemisorption and
 diffusion 93–106

with directional removal step and
 modification by reactive layer
 deposition 106–110
 with directional surface modification
 step 91–92

b

back end of line (BEOL)
 etch 189–191
 module 171
 bias power 136
 bias pulsing 136, 259
 binary collision approximation (BCA)
 simulation approach 16
 bond termination effect 147
 boron phosphorous silicon glass (BPSG)
 47
 Bose–Einstein statistics 13
 bottom anti-reflective coating (BARC)
 175
 bounded plasma system (BPS) 235
 bulk sputter coefficient 100
 bulk sputtering 134, 135

c

Cabrera–Mott (CM)
 diffusion 148
 oxidation models 23, 25, 26
 capacitively coupled plasma 238
 argon 239, 248
 CF_4 plasma 240
 particle-in-cell (PIC) models 240

- capacitively coupled two electrode RF plasma system 245
 - CCP RIE reactor
 - cathode and anode areas 247
 - electron density dependence on RF frequency 248
 - RF powered cathode and grounded walls 247
 - CD microloading 165
 - chelants 48
 - chelation 48
 - chemical downstream etching (CDE) 35
 - chemical etching techniques 1
 - chemically assisted ion beam etching (CAIBE) 36, 228
 - chemically assisted sputtering 136, 138, 139, 146, 157, 193
 - chemically enhanced etching 11, 94
 - chemically enhanced sputtering
 - mechanism 94
 - chemical plasma etching 2
 - chemical sputtering 138
 - chemisorption 13, 43
 - Child-Langmuir law 244
 - Cl_2/Ar^+ ALE FinFET gate etch process 125
 - Coburn–Winters synergy
 - experiment 134
 - collision cascade theory 16, 18, 94
 - commercial CCP reactors 250
 - complementary
 - metal–oxide–semiconductor (CMOS) 185
 - conductive bridge RAM (CBRAM) 216
 - contact etch 187
 - continuous flow stirred tank reactors (CFSTR) 180
 - copper damascene interconnect
 - approach 189
 - critical dimension (CD) 9
 - cryogenic etching 163
- d**
- Deal-Grove (DG) based oxidation models 23, 25
 - Debye length 236
 - deep trench dynamic random access memory (DRAM) devices 27
 - density functional theory (DFT)
 - first-principles simulations 54
 - deposition enhanced selectivity 156
 - deposition reactions 155, 169
 - desorption 13
 - dielectric anti-reflective coating (DARC) 171, 174
 - differential charging 152
 - diffusion process 68
 - diffusive reactant fluxes 181
 - directional ALE 91
 - archetypical system for 93
 - carbon materials 125
 - ideal window 97
 - ion assisted 95
 - process window of 95
 - of SiO_2 110
 - smoothing properties of 120
 - directional atomic layer etching 38, 135
 - direct redeposition 143
 - dissociative adsorption 12, 14
 - dissociative ionization 234
 - dry etching 7, 8, 11
 - dual frequency sheaths 250
- e**
- edge placement error (EPE) 10, 166
 - Elay-Rideal reaction 58
 - Elay-Rideal surface reaction
 - mechanism 15
 - electron energy distribution function (EEDF) 251
 - electron heating 251
 - electronic stopping 21
 - electron impact dissociation and ionization 234
 - electron-ion plasma 262
 - electron temperature 234
 - electrostatic chuck (ESC) 111
 - EPC non-uniformity 111
 - equivalent circuit model 246

- etching 7, 8
 - of copper 92
 - and diffusion 22
 - directional 29
 - history 1
 - implantation effects 21
 - of semiconductor devices, projected ranges and straggles 22
 - thermal 49
- etching per cycle (EPC) 8
- etching profiles 9, 10
- etching rate (ER) 8, 110
- etching rate non-uniformity (ERNU) 9
- etching technologies
 - electron assisted chemical etching 271–273
 - electron stimulated ALE 272
 - photon assisted chemical etching 273–275
 - plasma etching 271
 - Si_3N_4 and SiO_2 272
 - thermal etching processes 272
- etch per cycle (EPC) 53
- extreme ultraviolet (EUV)
 - lithography 180
- f**
- ferroelectric random access memory (FeRAM) structures 163
- fin etch 182
- FinFET gates 117
- FinFET logic devices 77
- floating potential 236
- fluorination atomic layer etching 37
- fluorocarbon polymer 148
- fluosilicic acid 46
- g**
- gas tuning 182
- gate-all-around (GAA)
 - InGaAs nanowires 78
 - stacked silicon nanowire fabrication 89
 - transistors 182
- gate etch 184
- gate first approach 185, 186
- Gaussian distribution 21
- Gibbs free energy 15
- graphene films 191
- grid sources 263
- ground electrode 263
- growth per cycle (GPC) 8
- h**
- hafnium aluminate thin films 186
- HBr/ Cl_2 / O_2 etching process 159
- hexafluoroacetylacetone (Hhfac) 49
- high energy directional ALE approach 118
- i**
- IBE reactors 263
- ICP plasma reactors
 - electric and magnetic fields 253
 - electron temperatures 254
 - schematic illustration 255
 - semiconductor device manufacturing 254
- impact parameter 16
- implantation effects, on etching 21
- “inboard/outboard” effect 225
- inductively coupled plasma (ICP) 252
- infinite selectivity 113
- instantaneous sputtering rate 100
- interatomic potentials 16
- intrinsic selectivity 9, 154
- ion angular distribution (IAD) 252
- ion assisted deposition technologies 172
- ion beam etching
 - applications 226–228
 - mechanism and performance metrics 225–226
- ion beam source with grids 265
- ion energy 100
- ion energy dispersion 242
 - frequency and mass dependence 242
- ion energy distribution (IED) 256
- ion etching chemical sputtering 133

ion flux 100
 ion-ion plasmas 259
 ion-neutral synergy 95
 ion shadowing 151
 ion transport 31
 isotropy
 defined 70
 etching 1, 9

k

keto tautomeres, structural
 formulas 48
 Knudsen transport 28, 71

l

Langmuir–Hinschelwood
 mechanism 48
 surface reaction mechanism 15
 Lateral etching 169
 Lennard–Jones diagram
 for dissociative adsorption 12
 for radical tching 86
 for thermal etching 14
 Lennard–Jones potential, for
 adsorbent–adsorbate system 11
 linear DG parameter 24
 line edge roughness (LER) 10, 169
 line-of-sight deposition 157
 line width roughness (LWR) 10, 169
 litho-etch-litho-etch (LELE) 175
 low energy ion spectroscopy (LEIS)
 33
 low temperature plasma 231
 LSS-theory 21

m

Magnetic Random Access (MRAM)
 memories 23
 mandrel patterning 178
 Metal Oxide Resistive RAM
 (OxRAM) 216
 Mixed Mode Pulsing (MMP) 135
 molecular dynamics simulations 85
 Monte Carlo modeling 209
 Moore’s Law 3

Mott potential 25, 46
 multi-state pulsing 137

n

n-doped silicon etches 147
 negative ions 137
 negative tone spacer double
 patterning 177
 neutral ARDE 28
 neutral fluxes 146
 neutral shading effect 28
 neutral transport 28
 non-equilibrium plasmas 232, 235,
 236, 251
 characteristics 233
 electron energy distribution function
 for 234
 parameters for 232
 non-thermal plasmas 232
 non-uniform redeposition 143
 non-volatile materials 163
 nuclear stopping 21

o

odd-even effects 178
 Ohmic heating 252
 OPOP channel hole etching 209
 Optane® 212
 Ovonic Threshold Switch (OTS) 212
 oxidation atomic layer etching 37
 oxidation of metals, experimental and
 modeling results 26
 oxygen ion diffusion 25

p

particle-in-cell (PIC) models 240
 passivating effect 177
 patterning etching processes 182
 performance metrics 110
 phase change memory (PCM) 23, 211
 phase change random access memory
 (PCRAM) 211
 photon induced thermal desorption 274
 photoresist mask 189
 physical sputtering 2, 103, 146

- physical sputtering process 225
 - physisorption 11, 43
 - PIC Monte Carlo simulations of RF discharges 249
 - plasma 231
 - plasma assisted thermal isotropic ALE 38, 74
 - plasma deposition 157
 - plasma electrode 263
 - plasma etching 2, 271
 - plasma frequency 238
 - plasma grid technology 263
 - plasma pulsing 38, 105, 135, 136, 259
 - plasmas capacitively coupled plasmas 237
 - plasma sheath 145
 - plasma technology 4
 - plasma voltage/potential 237
 - plasma VUV light 170
 - polymer covered sidewalls 153
 - Polymer enhanced selectivity 155
 - polymerizing passivation gases 145
 - polymer pre-cursors 153
 - process surface modification 134
 - projected range (implantation) 21
 - pulsed RIE process 38
 - pulse frequency 274
- q**
- Quantitative mass spectroscopy 143
- r**
- radical etching 35, 94, 134, 263
 - ARDE 87
 - benefit of 85
 - critical dimension 88
 - ERNU 87
 - etching rate 86
 - Lennard-Jones diagram for 85
 - post etch treatment chambers 88
 - profile 87
 - selectivity of 87
 - silicon nanowires/nanosheets formation 88
 - of silicon nitride 88
 - temperature process window for 86
 - reaction assisted desorption 37
 - reaction products, transport of 34
 - reactive fluorocarbon polymer layers 194
 - reactive ion beam etching (RIBE) 36, 138, 228
 - reactive ion etching
 - applications
 - aspect ratio 174
 - device type 174
 - IC manufacturing modules 174
 - materials 173
 - ARDE 150–154
 - CD control 165–168
 - chemical sputtering 138
 - DRAM capacitor cell etch
 - amorphous silicon 200
 - angular distribution of scattered ions 196
 - bowing and twisting and distortions 204
 - deep silicon etching 191
 - deposition precursor flux and profile 199
 - dominant etching mechanism 192
 - energy distribution of scattered ions 197
 - high aspect ratio dielectric etching 193
 - ion scattering and neutralization 193
 - isotropic etching 192
 - mask sputtering and redeposition 202
 - necking and bowing 199
 - neutral depositor flux 200
 - physical and chemical sputtering 197
 - reactive fluorocarbon polymer layers 194
 - semi-empirical profile simulator 198
 - sidewall deposited fluorocarbon film 206

- reactive ion etching (*contd.*)
 - sidewall roughness 204
 - silicon oxide capacitors 192
 - SiO₂ capacitor cell etching 192
 - SiO₂ contact holes 206
 - thermal neutral flux 194
 - twisting and deformation 205
 - ERNU 150
 - etching rate 144–150
 - etching species 161
 - extreme ultraviolet (EUV)
 - lithography 180
 - logic device
 - BEOL etch 189–191
 - contact etch 187–189
 - gate etch 184–187
 - spacer etch 187
 - LWR/LER 169–173
 - mixed layer formation 141
 - phase change memory (PCM) 211
 - profile control 156–157
 - resistive RAM devices 216
 - role of etching products 143–144
 - selectivity 154–156
 - self-aligned patterning 174–179
 - sidewall passivation 157–161
 - simultaneous fluxes 133
 - simultaneous species fluxes
 - bias power 136
 - bias pulsing 136
 - chemical/chemically assisted sputtering 136
 - Coburn-Winters synergy
 - experiment 134
 - cyclic RIE techniques 135
 - directional ALE 135
 - gas flow and pressure 135
 - ion-neutral synergy 133
 - Mixed Mode Pulsing 135
 - multi-state pulsing 137, 138
 - negative ions 137
 - neutral etching rate 134
 - neutralized ions 138
 - process surface modification 134
 - reactive layer deposition 135
 - silicon etching 133
 - synchronous pulsing 137
 - surface smoothness 168
 - temperature 162–165
 - 3D NAND devices 208
 - reactive ion etching (RIE) 2, 232
 - Redeposition 143
 - Reflectometry 156
 - remote plasmas 237
 - resistive Random Access Memory (ReRAM) 78
 - resistive sheath 238
 - resistive RAM devices 216
 - RIE methods 35
 - roughness propagation 170
- S**
- scattering ions 193
 - selectivity, for deposition process 76
 - selectivity, for etching process 77
 - self-aligned double patterning (SADP) 176
 - self-aligned quadruple patterning (SAQP) 179
 - self-bias 237, 261
 - self-limitation, ALE 36
 - shadowing effect 31
 - Shaped Waveform Bias 256
 - sheath formation, in bounded plasma 235
 - sidewall image transfer (SIT) 176
 - sidewall passivation 157
 - sidewall scattering 33
 - sidewall surface collisions 138
 - silicon ALE 93
 - silicon doping 23
 - silicon fluoride 143
 - silicon oxide capacitors 192
 - silicon oxynitride (SiON) 177
 - silicon sputtering rate and reflection coefficient 32
 - simultaneous etching 142
 - Si₃N₄ gate spacer etching 123
 - single Knock-on mechanism 17
 - Si₃N₄ spacer etching 117

SiO₂ ALE 106
 source divergence 225
 source-power-only regime 236
 source pulsing 260, 261
 space charge sheath 235
 spacer deposition 178
 spacer etch 187
 spacer etching 178
 spacer-on-spacer (SOS) technique 179
 spatial afterglow 262
 spontaneous reactions 15
 sputtering 15
 collision cascade theory 16, 18
 of multi-component materials 20
 thresholds for argon bombardment of
 materials 18, 19
 sputtering coefficient 100
 sputtering threshold 16
 sputtering yield 17
 sticking coefficients 28, 118
 stochastic electron heating 251, 252
 stopping mechanisms 21
 storage class memory (SCM) 210
 straggle effect 17
 suppressor electrode 263
 surface blocking 64
 surface channeling 33
 surface coverage 100
 surface diffusion 30, 121
 surface modification method 35
 surface reactions 14
 surface smoothness 3, 97, 120
 synchronous pulsing 137

t

tailored waveform bias (TWB)
 256–259
 temperature cycling 274
 thermal etching 36, 47, 94, 134
 ARDE 45
 critical dimension 44
 ERNU 43–44
 etching rate 43–44
 intrinsic etching 44
 mechanisms of 43

 profile 44
 of silicon by fluorine 45
 of silicon with XeF₂ 46
 temperature process window 44
 thermal isotropic ALE 51, 62, 94,
 112, 127
 area selective deposition 75–77
 chelation/condensation 54–55
 conversion ALE 58–60
 critical dimensions control 73–74
 etching rate 62–67
 etch rate non-uniformity 67–69
 lateral memory devices, formation of
 77–79
 ligand exchange ALE 55–58
 plasma assisted 74
 profile performance and ARDE
 70–73
 selectivity 69–70
 surface modification 52
 surface smoothness 74
 temperature process window for
 51, 53
 using temperature cycling 52
 thermal isotropic atomic layer
 etching 38
 thermal isotropic etching
 with ligand exchange reaction 63
 thermalization 195
 thermal neutral flux 194
 3D NAND flash memory 77
 3D NAND technologies 208
 through silicon via (TSV) 162
 time-dependent sheaths 244
 time dependent sheath voltage 239
 time domain processing 3
 tortuosity 70
 transformer coupled plasma (TCP)
 252
 transistor gate technology 185

u

ultra-high vacuum (UHV)
 experiments 273

V

- vapor etching 43
- vertical device integration 77
- voxel-slab models 107

W

- Wehner spots 15
- wet etching 1

