

# Index

Note: Page numbers followed by 'f' and 't' refer to figures and tables respectively.

## A

Accelerator surface diffusion, 241  
Acetylacetone, 171  
Acid-bath chemistry, 177  
Adherent surface coating, 73  
Adhesion promoter, 270, 316  
Adsorption, 148  
Agglomeration of polycrystalline NiSi layer, 126  
Air bridge Cu interconnects, 153–154  
    methods of simulation  
        calculation of effective elastic modulus, B, 157  
        electrical simulation, 156  
        model structure, 154  
        results and discussion, 160  
        stress simulation, 157  
    volume-averaged stresses, 162  
Air-gap formation method, 149f  
Al/Cu wiring, comparison, 278f  
ALD, *see* Atomic layer deposition (ALD)  
ALD TaN, step coverage of, 215f  
Alloy, selection rules of, 140f  
Al-negative patterning *vs.* single damascene-positive patterning, 9f  
Amyloid nano-fibrils, self assembly  
    aromatic dipeptide nanotubes, identification, 533–534  
    formation of nanostructures, 533f  
    aromatic homo-dipeptides, modified types, 535–536  
    nano-spheres formation, aromatic dipeptides, 535  
    peptide building blocks, technological advantages of, 536  
    peptide tubes, technological applications, 534–535  
    coaxial nanocables formation, 534f

    role of aromatic residues, 531–532  
Anode blanks, pilot plant production, 77f  
Anti-reflective layer (ARL), 281  
Area routers, 43  
Atomic layer deposition (ALD), 32, 107, 169, 178, 198–199, 264, 277  
    application in high aspect ratio structures, 214f  
    behaviors, 213f  
    characteristics of, 209f  
    cycle, steps of, 208f  
    ULSI manufacturing, 207–218, 217–218  
        ALD cycle, 207  
        ALD process window, 208  
        applications, 210  
        PLC, 218  
Autocatalytic ELD, 222  
Axial stress difference, 162

## B

Back-end-of-line (BEOL), 82, 275  
    ALD TaN grown on SiO<sub>2</sub>, 215f  
    applications, 214–217  
        ALD ruthenium adhesion layer, 216  
        dual-damascene metallization, 215  
        pentakis-(dimethylamido)tantalum (PDMAT), 214  
    Cu wiring, 291  
    low-cost processing, 291  
    low-*k* integration, 291  
    low-*k* materials, 277–278  
    metallization issue, 278  
    SiV failure mode, 279f  
65 nm/45 nm technology node, 284  
    controllability, 285  
    cross section SEM of 65nm node, 285f  
    EB curing process, application, 285–290  
    integration issues, 284–285

- Back-end-of-line (*cont.*)  
 90 nm technology node, 279–280  
 patterned low-*k* films, characterization,  
 293–294  
 robust process development, 291–293
- Back End Process (BEP), 145
- Back grind, 148
- Barrier layer, 5, 259
- Barrier self-formation/sputtered Cu alloy films,  
 138*f*
- Bath components controlling and monitoring  
 tools, 435  
 analysis of chemical constituents, 436  
 model-based closed-loop chemical  
 control system, 443*f*  
 open-loop replenishment system, 442*f*  
 replenishment and system designs,  
 442–443  
 titration, 436–437  
 X-ray fluorescence, 437
- chemical management process,  
 automation, 435
- electroanalytical techniques, 437  
 chronoamperometry, 439  
 CPVS, 437–438  
 CVS, 437–438  
 ion-specific electrodes, 440  
 liquid chromatography, 440–441  
 mass spectrometry, 441  
 ORP electrodes, 440  
 overview of, 441–442  
 photometric techniques, 440  
 pH probe, 440  
 pulsed cyclic galvanostatic analysis  
 (PGCA), 439  
 spectrophotometric techniques, 440
- electrolyte components, classification,  
 435–436
- Bath constituents used for ELD, 227*t*
- BEM, *see* Boundary element  
 method (BEM)
- Benzocyclobutene (BCB), 84, 278
- BEOL, *see* Back-end-of-line (BEOL)
- BEP, *see* Back end process (BEP)
- Bias thermal stress (BTS), 95
- Bio-inspired biological nano-assemblies, 531
- Biological and related templates of ELD,  
 227*t*–228*t*
- Bonding process, 85
- Boundary element method (BEM), 240
- Boundary value problem (BVP), 242
- Brightening mechanism, 241
- BTS, *see* Bias thermal stress (BTS)
- Bumping, 148
- “Buried oxide,” *see* Insulating silicon dioxide
- Butler–Volmer equation, 224, 240
- C**
- CAD, *see* Computer-aided design (CAD)
- Capacitance–voltage curves, 113*f*
- Capping layer, 148
- Carbon-doped silicon oxide (SiOC), 266
- Catalyst deactivating leveler, 241
- CD, *see* Critical dimension (CD)
- CEAC, *see* Curvature-enhanced accelerator  
 coverage (CEAC) mechanism
- Chemical mechanical polishing (CMP), 9, 64,  
 84, 148, 183–186, 259, 343, 344*f*  
 application of Cu-CMP, 345–347  
 dishing and erosion problems, 347*f*  
 five layers MPU, 346*f*  
 planarization performances defined,  
 347*f*  
 tool, 346*f*  
 categorization, PVT dependence, 349–350  
 conventional, 259
- Cu processing, 257, 343
- dissolution law, chemical etching (CE), 355  
 principle of etching polishing, 355*f*  
 removal rate, 354, 355
- polish principles and performances, 348
- principles, 373*f*  
 planarization diagram, 356*f*  
 planarization technologies, types,  
 351–352, 352*f*; 355–356  
 polishing, 352*f*  
 slurry requirements, 348–349  
 PVT dependence, 349*f*  
 subsystems, 345, 345*f*  
 surface cleaning, 350, 350*f*
- Chemical-selective etching, 125
- Chemical vapor deposition (CVD), 6, 17, 32,  
 145, 169, 185–186, 198, 241, 264,  
 277  
 types, 145
- Chip-scale package (CSP), 80
- CMOS, *see* Complementary metal oxide  
 semiconductor (silicon) (CMOS)
- CMP, *see* Chemical mechanical polishing  
 (CMP)
- Co alloy capping process/systems  
 crystalline/amorphous dependence,  
 449–450  
 deposition chemistry, 450–451
- Co alloy capping tools, 445  
 application, 446–447

- Black's law, 447
- EM improvement results, 447*t*
- copper damascene process, 445
  - electromigration (EM) void, 445*f*, 446*f*
  - properties and requirements, film
    - crystalline/amorphous dependence, 449
    - sample, 448*t*
    - TDDB, 448
- Coefficient of thermal expansion (CTE), 153
- Cold-pressing technology, 78
- Complementary metal oxide semiconductor (silicon) (CMOS), 3, 47
  - n-MOS and p-MOS transistors, 15
  - trends in miniaturization
    - Moore's law, 23–25
    - roadmaps, 25–27
    - scaling and power dissipation, 29–32
    - scaling theory, 27–29
- Computer-aided design (CAD), 42
- Conductor, ULSI ICs, 5
- Copper damascene module issues, 276*f*
- Copper dual damascene technology, 359
  - nitric acid (HNO<sub>3</sub>)-base, 364–367
    - addition of citric acid, 365
    - advantages in HNO<sub>3</sub>-BTA slurry, 365
    - effect of BTA, 367*f*
    - evaluation of anodic current transient measurement, 367*f*
    - optimum BTA, concentration, 364
    - potentiodynamic curves of copper, 366*f*
  - peroxide-base, 368–372
    - anodic current peak range, 370*f*
    - anodic potentiodynamic curves, 372*f*
    - effect of BTA, 371*f*
    - etching rate of copper, 368–369
    - utilization of H<sub>2</sub>O<sub>2</sub>, 368
- Copper electrodeposition, 67–68
- Copper interconnects, electrochemical
  - processing tools, 389
  - damascene capping, electroless processes, 393–394
  - dual damascene process, 389–390
  - electropolishing for planarization, 392–393
  - methods for improving copper electromigration, 394
  - novel processing methods (node and beyond), 391–392
  - PECVD Si(C) N cap technology, 393
  - processing methods, (node and beyond), 391–392
  - PVD-sputtered Ta(N) liner, 393
  - redundant ruthenium (Ru) liner approach, 394
  - tooling requirements, 390–391
- Copper metallization/motivation, 93–94
- Copper post-CMP cleaning, 257
- Copper-to-copper via-first cross section, 85*f*
- Copper wiring, formation, 149
- Core computation engine, 156
- Co-rich phase silicide, 125
- Courant–Freidricks–Levy number (cflNumber), 251
- Critical dimension (CD), 260, 265, 282
- CSP, *see* Chip-scale package (CSP)
- CTE, *see* Coefficient of thermal expansion (CTE)
- C54-TiSi<sub>2</sub>/CoSi<sub>2</sub>/NiSi, properties, 124*t*
- Cu damascene interconnects
  - hard masks (HM) process, 305–308
    - alignment shift between upper lines (M2) and vias, 306*f*
    - double-layered/triple-layered HM, 305*f*
    - leakage currents between adjacent lines, 308*f*
    - SEM micrographs, shouldering of LTS and LER, 307*f*
    - sidewall protection layer formation, 307*f*
  - limitations of multi-hard mask (MHM) processes, 308
  - lithography process
    - pure organic/inorganic ILD film, 301*f*
    - SEM micrographs, 300*f*
    - technical trends, 300*f*
  - photoresist (PR) mask, 302–305
    - cross-sectional SEM micrographs, 303*f*
    - Mises stress distributions and electrical properties, 304*f*
    - via-first process for inorganic low-*k* ILD films, 302*f*
    - via-first process with RM, formation mechanism, 304*f*
    - via poisoning, 303*f*
- Cu dual damascene process, 9
  - vs. Al lithography, 10
- Cu metallization/difficulties of implementing, 94–98
  - copper adhesion to dielectric, 96
  - copper diffusion/degradation of dielectric, 95–96
  - copper diffusion/reaction with Si, 96–98
  - copper passivation, 96

- Cu metallization (*cont.*)  
 diffusion barrier and capping (or cladding) layer, 94  
 processing, 98
- Cu metallization/diffusion barriers/evaluation of, 107–114  
 analytical techniques  
   SIMS, detection limits of, 108  
 electrical devices/evaluation of diffusion barriers, 109–111  
   metal-oxide-semiconductor (MOS) capacitor, 111  
   reverse-biased Schottky diodes, 110  
   reverse-biased shallow p–n junctions, 109  
   Schottky diodes, 110  
 equilibrium C–V curve, 113  
 flat-band voltage of equilibrium capacitance–voltage, 112  
 hybrid organosiloxane polymer, 108  
 microscopic-based techniques, 108  
 plasma enhanced CVD (PECVD), 112  
 quasi-static C–V measurements, 114
- Current–voltage plots of Cu/TiN/p–Si, 111 *f*
- Curvature-enhanced accelerator coverage (CEAC) mechanism, 241, 242, 244
- Cu thin films/grain growth mechanism, 135–139  
 nano-scale self-formation/Ti diffusion barrier layers/Cu(Ti) alloy films, 138–140  
 annealing and low film resistivity/Cu(Ti) alloy films, 140  
 melting point reduction, 140  
 Rutherford backscattering spectrometry, 139  
 sputter-deposition techniques, 138  
 TEM-EDS elemental mapping image, 139  
 strain energy criterion model, 135  
 TEM experiment, 137
- CVD, *see* Chemical vapor deposition (CVD)
- Cyclic pulsed voltammetric stripping (CPVS), 437–438
- Cyclic voltammetric stripping (CVS), 437
- D**
- Damascene, 269  
 capping, electroless processes, 393–394  
 damage-free process, 269  
 low-k integration challenges, 266  
 plating, 64  
 process, 8, 259, 263  
 technique, 257, 259
- Dc plating, 66
- Delaminated area of Cu film, 269 *f*
- Density of state (DOS), 293
- Deposition chemistry, 452–455  
 brush clean chambers, 455 *f*  
 chambers, 455 *f*  
 cleaning and activation chambers, 454 *f*  
 functions of chemicals, 451  
 UV–Vis spectroscopic measurement, 453 *f*
- Deposition process and tools, electrochemical, 397–408  
 damascene copper electrodeposition, 403–407  
   component separation of plating chemistry, 403–405  
   current density profile, 404 *f*  
   potential field distribution technique, 402–403, 403 *f*  
   rinsing procedure, wafer, 404–405  
 electro chemical processes, types of, 400–401  
 electrografting, 406–407  
 electrophoretic deposition, 407–408  
 processing chamber of wafer, 399–400  
   chamber configuration of ECMD, 399  
   properties of fountain reactor, 399  
 safety guidelines, electro chemical processes, 400  
 semiconductor and microelectronic processes, 405–406  
 through-mask electrodeposition, 405–406  
   conductive base layer stack, 406–407  
   general class of ECD processes, 405 *f*  
   using photoresist, 406  
 tool configuration, 400  
   safety guidelines, 400  
   safety of tool design, 400  
 wafer handling automation, 397–398  
 wafer processing equipment, 397
- DG-FET, *see* FinFET
- Dielectric constant ( $k_{eff}$ ), 265, 269, 275  
 effective, 161 *f*  
 extraction of effective, 157 *f*  
 for single-via level model structure, 161 *f*  
 trends, 276 *f*
- Dielectric films, 264
- Die-on-wafer, 81  
 3D integration, 81 *f*
- Diffusion barriers, 98–107  
 amorphous barriers, 104  
 deposition methods, 106–107  
 passive metallic thin films, 99–101

- diffusion kinetics, 99
  - failure time of barrier, 99
  - high segregation factor, 99
  - significant Cu diffusion, 101
  - sacrificial barriers, 103–104
  - self-assembled molecular layers, 105–106
    - ionized metal plasma (IMP), 107
    - PVD TaN film, 107
    - self-assembled molecular (SAM), 105
    - synchrotron X-ray diffraction analysis, 107
    - vapor or wet-chemical methods, 106
  - self-forming barriers, 104
  - single crystalline barriers, 104
  - “stuffed” barriers
    - tantalum films/high-vacuum (HV), ultra-high-vacuum (UHV), 103
    - TiN, diffusion barrier for Al metallization, 103
    - TiN/Al/TiN for Cu metallization/multi-layered diffusion barrier of, 102
  - “thermal budget,” 99
  - thermodynamically stable barriers, 101–102
    - TaN, by PVD and CVD, 101
  - Diffusion driven theory of leveling, 239
  - 3D integration, ULSI interconnects, 79
    - BEOL-based wafer-level, 84
    - types, 80
  - Double-gate MOSFET, 36
  - Drain-induced barrier lowering (DIBL), 28
  - DRAM, *see* Dynamic random access memories (DRAM)
  - Drift-diffusion model, 20
  - 3D stacked imager circuit, 88
  - Dual damascene process, 9
    - barrier/etch-stop SiCN process, 283
      - cross second TEM images, 284*f*
      - modified edge liftoff test (m-ELT), 284
      - strength of adhesion, 284
    - plating, 65
    - SiO<sub>2</sub> capping, 282
      - photoresist poisoning process, 283*f*
      - SiOC/SiCN, impact, 283*f*
    - via-first patterning, 281
      - DD shape, comparison, 282*f*
  - Dynamic random access memories (DRAM), 5, 211
- E**
- EB curing process, application
    - Par/SiOC hybrid scheme, integration, 288
    - porous Par/SiOC, hybrid DD, 290*f*
    - SiV performance of 45 nm node, 289*f*
    - SiV test results, 289*f*
  - porous low-*k* MSQ evaluation, 286
    - EB curing time, function, 287*f*
    - EB total dose, function, 286*f*
    - FT-IR spectrum, 287*f*
    - interface fracture energy (G<sub>c</sub>) vs. EB total dose, 288*f*
  - ECD, *see* Electrochemical deposition (ECD)
  - ECMD, *see* Electrochemical mechanical deposition (ECMD)
  - ECP, *see* Electrochemical polishing (ECP)
  - EDTA, *see* Ethylenediaminetetraacetic acid(EDTA)
  - EELS, *see* Electron energy loss spectroscopy (EELS)
  - Elastic modulus, 160
    - for multi-via level structures, 165*f*
  - ELD, tools and processes, 413
    - copper
      - chemistry of, 414–415
      - deposition process, 418–419
      - palladium and direct surface activation, usage of, 417–418
      - sensitization and surface activation, 417
      - substrate and self activation, 422
    - design criteria, 429
    - gap filling, 418
    - gold, 425
      - autocatalytic deposition, 426–428
      - cyanide base, 425–426
      - immersion deposition, 426
      - non-cyanide, 428–429
    - immersion reactors, 429
    - nickel
      - aluminum substrates and activation, 422–425
      - catalyzed deposition, 428
      - deposition process, overview of, 425
      - deposition and chemistry, 419–421
      - substrate activation, 421
  - Electrical chemical mechanical polisher (ECMP), 354
  - Electrical degradation, NiSi, 126
  - Electrical resistance of Al, 258
  - Electrical resistivity, 259
  - Electrical resistivity/nitrogen content of TaN<sub>x</sub> films, 102*f*
  - Electrochemical deposition (ECD), 279
  - Electrochemical mechanical deposition (ECMD), 392

- Electrochemical polishing (ECP), 258  
 Faraday's law, 353–354  
 principle of, 353 *f*
- Electrochemical processes for ULSI  
 Interconnects, 183  
 copper plating chemistry, 186–198  
 Bath composition, 189 *t*  
 Bath composition for void-free filling, 186–187  
 bis(3-sulfopropyl)disulfide (SPS), 188–189  
 bottom-up, 186–187  
 Cannizzaro reaction, 195–196  
 cathodic cross-sectional SEM, 193  
 cathodic polarization *f*, 192  
 chemistry of copper plating bath, 188–189  
 copper deposition mechanism and kinetics, 187–188  
 copper electrodeposition for trench filling, 186  
 copper electroless deposition for trench filling, 194–195  
 electroless deposition reactions, 195–196  
 formaldehyde (HCHO), 195–196  
 Janus Green B (JGB), 188–189  
 mechanism of electroless copper deposition, 195–196  
 mechanism of void-free filling effect of additives, 193–194  
 polyethylene glycol (PEG), 188–189, 196–198  
 reaction mechanism: effect of additives, 189–192  
 superfilling, 188–189  
 superfilling by electroless copper deposition, 196–198  
 dual damascene process, 184–186  
 electrochemical process for seed layer formation, 198–201  
 barrier layer formation/seedless copper filling, electroless deposition, 200–201  
 electroless deposition for formation of seed layers, 198–199  
 seedless copper electrodeposition on barrier materials, 199–200  
 single damascene, 184–186  
 single/dual damascene processes, 186  
 subtractive etching process/damascene process, 184 *f*, 185
- Electrochemical process integration  
 BEOL technology advanced, 257  
 CMP, 257  
 copper post-CMP cleaning, 257  
 Cu metallization PVD barriers, 257  
 damascene concept/process, 257  
 electrochemical view of copper chemical mechanical polishing, 257  
 lithography for Cu damascene fabrication, 257  
 low-*k* dielectrics, 257
- Electrochemical view of copper CMP, 257, 359–377  
 advantage characteristics of copper, 359  
 ammonium hydroxide-base, 361–364  
 anodic potentiodynamic curves, 362 *f*  
 etching rate of copper, 362–363  
 linear polarization of measurement (LPR), 361  
 open circuit potential (OCP), 361  
 oxidants additions, 361  
 polarization curves, 362 *f*  
 surface morphology, 363 *f*
- carbonate- and sorbate-base, 372–375  
 addition of oxidizer, 373  
 anodic polarization of, 375 *f*  
 anodic potentiodynamic curves, 374 *f*  
 effect of BTA, 373  
 evaluation of anodic current transient measurement, 375 *f*
- Electrochemistry, 257
- Electrode/electrolyte interface, 241
- Electrodeposition, 63, 241  
 advancement, 63–64  
 advantages, 63  
 application, 63–64  
 changes in process conditions, 64  
 copper electrodeposition, 67–68  
 dc plating, 66  
 mass transport conditions, 65–66  
 patterned plating, scales of, 65  
 potential distribution, 67  
 pulse plating, 66  
 pulse reverse plating, 67  
 through-hole plating, 67  
 types of electroplating in fabrication, 64
- Electroless deposition (ELD), 176  
 autocatalytic, 222  
 bath components, 227 *t*–228 *t*  
 bath constituents used for, 227 *t*  
 biological and related templates of, 227 *t*–228 *t*  
 on nanoscale object, schematics of, 223 *f*  
 structure type of, 227 *t*–228 *t*

- Electroless deposition (ELD)/molecular scale, 221
- autocatalytic ELD of metals, 221
  - fundamentals, 223
    - Butler–Volmer equation, 224
    - nanoscale deposition, special of, 225
    - Nernst equilibrium, 223
    - steering macroscopic, 224
  - galvanic plating, contrast, 222
  - macroscopic, 226
    - biomolecules as templates, 229
    - confinement plating, 228
    - confinement plating in biomolecules, 231–232
    - sensitization, Pd and Pd/Sn colzoids, 226
    - nanoscale deposition, 222
    - scientific communities and, 221
    - Tollens reaction, 221
- Electrolytic plating/electroplating/plating, 63  
*see also* Electrodeposition
- Electromigration (EM), 265, 281
- Electron beam (EB), 269, 285
- Electron energy loss spectroscopy (EELS), 293
- Electronic technology-based hierarchy, 4*f*
- Electron mean free path, 264
- Electrophoretic deposition (EPD), 73
- electrophoresis and, 73–74
    - process limitations, 73–74
    - theoretical basis, 74
  - potential applications, 74–78
    - conducting lines, 75
    - embedded passive components, 75–77
    - fuel cell technology, 75
    - solid electrolyte capacitors, 77–78
- Electroplating, additives, 65
- Element removal and reactivation technique, 157
- Elmore delay, 48–50
- EM, *see* Electromigration (EM)
- Embedded process, 259  
*see also* Damascene, technique
- “End of roadmap” technology, 176
- Energy-filtered (EF) images, 294
- Epitaxial alignment, NiSi, 127
- Epitaxial lateral overgrowth, 82
- Etching process, 156, 259, 260
- Ethylenediaminetetraacetic acid (EDTA), 195, 415
- Eulerian level set method (LSM), 241, 245, 246
- Eulerian techniques, 241
- F**
- Fabrication process, 269
- FEA, *see* Finite element analysis
- FEM, *see* Finite element method (FEM)
- FEOL, *see* Front-end-of-line (FEOL)
- FEOL/ITRS specifications, 211*t*
- Fick’s laws, 225
- FinFET, 36
  - structure and transistor, 37*f*
- Finite element analysis, 154, 157*f*
- Finite element method (FEM), 240
- Finite volume method (FVM), 241
- FiPy output, 251*f*
- Flat-band voltage of MOS capacitors, 113*f*
- Fluorine-doped silicon oxide (SiOF), 266, 277
- Fourier transformed infrared spectroscopy (FT-IR), 293
- Front-end-of-line (FEOL), 82
  - applications, 211–212
    - dynamic random access memories (DRAM), 211
    - equivalent oxide thickness (EOT), 211
    - gate dielectric leakage, 211
    - metal–insulator–metal (MIM) capacitors, 211–212
    - metal–insulator–silicon (MIS) capacitors, 212
    - metal organic precursors/hafnium amido compounds, 211
    - Moore’s law, 211
    - physical vapor deposition (PVD), 211
- FT-IR absorption spectra, 269
- “FUSI” (fully silicided gate), 32, 127
- FVM, *see* Finite volume method (FVM)
- G**
- Galvanic deposition, 224  
*see also* “Sensitization”
- Galvanic electrodeposition, 222
- Gas evolution of adsorption material (degas), 148
- Gate delay, 21, 258
  - versus* interconnect delay, 22–23, 23*f*
  - of logic inverter, 21*f*
- Ge atoms, segregation, 128
- Germanium and III–V channel devices, 35–36
- Graphite layer, 150
  - formation, 149
- Greenhouse issue, 257
- Grid2D object, 249
- H**
- HAR, *see* High aspect ratio (HAR)
- Heat conduction, 148

- High aspect ratio (HAR), 83  
 High-density interwafer, 87  
 High gas/metal penetration, 284  
 High moisture uptake, 284  
 High temperature storage (HTS), 290  
 HSQ, *see* Hydrogen silsesquioxane (HSQ)  
 Hybrid dielectrics, 266  
 Hydrogen-free reductants, 222  
 Hydrogen silsesquioxane (HSQ), 277  
 Hydrostatic stress, 158
- I**
- ILD, *see* Interlayer dielectrics (ILD)  
 IMP, *see* Ionized metal plasma (IMP)  
 Incubation delay, 209  
 "Induction period," 225  
 "Input switching threshold," 21  
 Insulating silicon dioxide, 34  
 Insulator between wiring, change of, 145  
 Insulator materials between wiring, change of, 146*t*
- Integrated circuit  
   invention of, 3  
   metallization, 94*f*
- Integrated metrology (IM), 479  
   benefits of, 480  
   closed loop control (CLC) process, 486–488  
     benefits of, 488  
     open-loop control using default polish time, 488*f*  
     PID algorithms, 486–487  
     real time adjustment, 486*f*  
     using default polish time, 489*f*  
     before using process control, standard deviation measurement, 489*f*  
   criticisms of process equipment  
     manufacturers (PEM), 480–481  
   end-users *versus* IM implementation, 480  
   evolution of, 481  
   limitations of, 479–480  
     copper CMP, 493  
   major components, 484  
   measurement accuracy  
     film thickness, 482–483  
     optical model, 483  
   return on investment, qualitative view  
     capital investment, 490  
     consideration factors, 490–492  
     cost saving attributes, 491  
     manufacturing advantages, 491–492  
     reduction of labor, 490  
     before using process control, standard deviation measurement, 489–490  
     software applications, 494  
     technology, 481–486  
     dry factory interface, 485*f*  
     latest generation IM tool specification, 486*t*  
     pre-metal dielectric (PMD) process, 493  
     refraction index, Spectrophotometer, 482*f*  
     shallow trench isolation, 492–493  
     typical optical scheme, spectral reflectometer, 484*f*  
     Wet NovaScan 210, 485*f*  
     tools installation, 481
- Interconnects  
   (dimensions of 32 nm), challenges, 4  
   performance issues, 7–8  
   process issues, 8–11  
   reducing resistance, 7
- Interconnects in ULSI systems  
   circuit models of interconnect, 45–52  
     area capacitance, 46–47  
     capacitive interconnect, 46–47  
     cross-capacitance, 46–47  
     electromagnetic wave propagation, 50–52  
     ideal interconnect, 45  
     inductive interconnect, 50–52  
     interconnect model types (from top to bottom), 46*f*  
     lumped/distributed RC stage, 48*f*  
     parallel-plate capacitor expressions, 46–47  
     RC tree, 50  
     resistive interconnect, 48–50  
   design approaches/techniques for interconnect problems, 55–58  
     circuit architecture, 58  
     layout optimization techniques, 57–58  
     metallization stack design, 55  
   interconnect metrics, 43–45  
     delay, 43–45  
     power, 43–45  
     reliability, 43–45  
     signal integrity, 43–45  
   interconnect scaling problem, 52–55  
     effective metal resistivity, 54  
   on-chip interconnect requirements, 39–43  
     blocks, 39–40  
     channel routers, 43  
     configurable interconnect, 40  
     cross section of metallization stack, 42*f*



- floorplan, 40*f*
  - global wires, highest levels, 40
  - local wires, low-level blocks, 40
  - Rent's rule, 41
  - routing tree, 43*f*
  - signal sinks, 43
  - signal source, 43
- power supply interconnect, 58–59
- Interconnect structures, fabrication, 153
- Interface delta function, 247
- Interface engineering targeting, 285
- Interface fracture energy ( $G_c$ ), 288*f*
- Interface topology, 241
- Interfacial fracture, 165
- Interlayer dielectrics (ILD), 93, 285
- International technology roadmap for semiconductor (ITRS), 25, 121–122, 145, 211, 216
  - challenges for interconnects, 4
  - near-term technology trend targets of, 26
- Intrinsic gate delay, 21–22
- Intrinsic leakage current, 125
- Ion-enhanced ash, 271
- Ionized metal plasma (IMP), 107
- Isolation layer, formation, 150
- ITRS, *see* International Technology Roadmap for Semiconductor (ITRS)
  
- J**
- Joule's heating ( $Q$ ), 258
- Junction leakage, 125
  
- K**
- $K_{eff}$  with respect to air gap, 160, 161*f*
- KGD, *see* Known-good-die (KGD)
- Kinetic regime of diffusion in polycrystalline materials, 100*f*
- KKA, *see* Kramers–Kronig analysis (KKA)
- Known-good-die (KGD), 81
- Kramers–Kronig analysis (KKA), 294
  
- L**
- Lagrangian approach, two-dimensional, 241
- Langmuir adsorption, 244
- Langmuir kinetics, 170, 173, 178
- Laplace equation, 240
- Large-Grained Cu Interconnects, 133–135
  - Cu thin films/abnormal grain growth, 133–135
    - bimodal grain growth, 133
    - FIB techniques, 135
- Large-scale integration (LSI), 3, 257
- Leakage current/function of time/copper on thermal oxide, 112*f*
- LER, *see* Line-edge-roughness (LER)
- Leveling theory, 239, 240
- Lewis base, 172
- Linear interpolation, 244
- Line-edge-roughness (LER), 260
- Lithography
  - for Cu damascene fabrication, 257
  - misalignment, 281
- Low- $k$  dielectric film, 257
  - basic properties, 327–330
    - cracking and delamination, 329*f*
    - effects of water adsorption, 330*f*
    - mechanical aspects, 328*f*
    - pore size distributions, 328*f*
  - CAP dielectrics, future trends, 337
  - deposition process, 325–327
    - analytical methods, 327*f*
    - technical issues and trends, 326–327, 326*f*
  - TEM micrographs of ULSI interconnect pitches, 326*f*
  - hardening and post-curing techniques, 330–332
    - EB/UV radiation and irradiation process, 331*f*
  - $k$ -value vs. mechanical properties, 332*f*
  - innovation materials and process, 332–337
    - criteria for porous stability, 334
    - durability ratio, 335*f*
    - plasma co-polymerization technology, 334–336, 337*f*
    - technological trends, 334*f*
    - UV curing method, 335*f*
- Low- $k$  materials, 7–8
  - for CVD, 147*t*
  - development, 145
    - change of insulator between wiring, 145
    - conditions for practical usage, 146
    - issues of porous low- $k$  materials, 148
    - porous low- $k$  material, 148
  - for SOG, 147*t*
  - variety, 277*f*
- Low mechanical strength, 284
- Low plasma resistance, 284
- LSI, *see* Large-scale integration (LSI)
- LSI implementation, 257
  
- M**
- Macroscopic ELD
  - biomolecules as templates, 229
  - “enhancement,” 229
  - “enzyme metallography,” 229

- Macroscopic (*cont.*)
- hydroquinone, standard reductant, 229
  - confinement plating, 228
  - popular substrates, 229
  - confinement plating in biomolecules, 231–232
    - Ohmic behavior, 231
    - Reches' silver, 231
  - fundamentals, 224–225
  - sensitization, Pd and Pd/Sn colzoids
    - “self-sensitizing,” 226
- Material design engineering, 285
- Maze routers, 43
  - see also* Area routers
- Mean free path (MFP), 278
- Mean time to failure (MTF), 283
- Mechanical friction, low-*k* film, 265
- Medium-scale integration (MSI), 3
- Melting point of Cu, 258
- MEMS, *see* Microelectromechanical systems (MEMS)
- Metallization patterning process, 68
  - see also* Dual damascene process, plating
- Metallorganic condensation, 171
- Metallorganic thermal decomposition, 171
- Metal–metal bond formation, 225
- Metal-oxide-semiconductor field-effect transistor (MOSFET), 15, 16*f*, 121, 127
  - characteristics, 19
  - “long-channel characteristics,” 18
  - novel devices, 36–37
  - source–drain current, 18
- Metal-oxide-semiconductor (MOS) transistor, 93
- Metal penetration, 270
- Methyl silsesquioxane (MSQ), 277, 285
- Microelectromechanical systems (MEMS), 63, 87
- Microporous non-conductor, 73
- Micro-processing units (MPU), 258
- Middle-of-Line (MOL) applications, 212–214
  - ALD W nucleation layers, 214
  - chemical vapor deposition (CVD), 212
  - tetrakis(dimethylamido)titanium (TDMAT), 212
- Mini-electron beam, 148
- “Mixed potential,” 223
- MnP-type structure (orthorhombic), 127
- Modified edge liftoff test (m-ELT), 28
- Modular assembly, 77
- Moletronics, nanoscale interconnects
  - technology
- carbon nanotubes (CNTs)
    - electronic structure, 514–515
    - geometric structure, 514–515
    - interconnect applications of CNTs, 516
    - tube-tube junctions, 516–518
    - mechanical properties of CNTs, 515
    - thermal properties of CNTs, 515
    - tube–metal contacts, 518–519
  - “Moore’s clock,” 23, 25*f*
    - pendulum, phases, 24
  - Moore’s law, 23–25, 64
    - scaling trend of DRAM cell area, 24*f*
  - MOS capacitor model, charge density, 16
  - MOS capacitors with CoPW diffusion barriers, 114*f*
  - MOS device and interconnects scaling physics
    - current regimes, 18–19
    - linear region, 17–18
    - saturated region, 18
    - subthreshold region, 19
  - digital signal propagation
    - gate delay, 21–22
    - gate delay *versus* interconnect delay, 22–23
    - trends in CMOS miniaturization, 23–32
  - mobility and carrier velocity, 20–21
  - MOSFET transistor
    - basic device physics, 15–17
    - technology, 17
  - new device structures and materials
    - germanium and III–V channel devices, 35–36
    - novel MOSFET devices, 36–37
    - silicon-on-insulator (SOI), 34
    - strained silicon and SOI, 34–35
    - strained-silicon MOSFET, 32–34
- MOSFET, *see* Metal-oxide-semiconductor field-effect transistor (MOSFET)
- MOS transistor, *see* Metal-oxide-semiconductor (MOS) transistor
- MPU, *See* micro-processing units (MPU)
- MSQ, *see* Methyl silsesquioxane (MSQ); Porous methylsilsesquioxane (MSQ)
- Multilayer photomask structure, 260
- Multilayer tape sandwich, 76
- Multi-via level air-bridge structure, for stress calculation, 159*t*
- Multi-via level model structures, 155*f*
- N**
- Nanoclustering method, 268
  - Nanometer-level pores, 266

- Nanopowder, 78
- Nanoscale deposition, 225
- Nanoscale interconnect technology
- alternative molecular system
    - charge transport mechanisms, 519–520
    - self assembly techniques, 520–522
  - architectures, 507–508
  - die-to-die integration, 509–510
  - hyper-integration, 508–509
  - moletronics, 511
    - carbon nanotubes (CNTs), 512–514
    - silicon wafers with BCB
      - bonds.(infrared image), 512*f*
    - wafer-to-wafer integration, 510–511
- Nanoscale objects, 222
- “Nanotechnology,” 226
- National Technology Roadmap for
- Semiconductors, *see* International Technology Roadmap for Semiconductor (ITRS)
- Nernst equilibrium, 223
- NiAs-type structure (hexagonal), 127
- Non-aqueous dispersion media, 74
- Non-volatile memory (NVM), 82, 83
- N-type MOSFET, 15
- charge regimes of MOS capacitor in, 16*f*
- Nucleation mode, C54-phase, 124
- NVM, *see* Non-volatile memory (NVM)
- O**
- Ohmic metal/semiconductor contact, 122
- Oxidation–reduction potential (ORP), 436, 440
- Oxide-to-oxide bonding, 85
- P**
- PAALD, *see* Plasma-Assisted Atomic Layer Deposition (PAALD)
- Palladium (II) hexafluoroacetylacetonate, 170
- structure, 172*f*
- Parasitic capacitance, 263
- Patterned plating, scales of, 65
- PCB, *see* Printed circuit board (PCB)
- PECVD, *see* Plasma-enhanced CVD (PECVD)
- PFM, *see* Phase field method (PFM)
- Phase field method (PFM), 246
- Physical vapor deposition (PVD), 186, 277
- barriers, Cu metallization deposition technique, 316–317
    - alternative methods, 317–318
    - self-formation, 317
    - sputter deposition, 316–317
  - diffusion barrier layer necessities, 311–312
  - driving force, types, 317–320
    - classification of metal, coefficient activity, 319*t*
    - Ellingham diagram, 318*f*
    - solute concentration , coefficient activity, 319*f*
  - metallurgical aspects, 312–316
    - bias thermal stressing (BTS) test, 314
    - conventional criteria, material selection, 312
    - diffusion barrier parameters, 313*t*
    - influence of contact angle, 315
    - influence of substrate surface condition, 316–317
    - resistivity and heat of formation of carbides, 315*t*
    - resistivity and heat of formation of nitrides, 314*t*
    - role of kinetics, 320
- Pixel-by-pixel processing, 87
- Planarization, advanced techniques, 459
- conventional methods (copper), 460–461
  - electrochemical polishing, 460
  - limitations, 459–460
  - mechanical depositions, 462–463
  - mechanism of ECMD, 463–469
  - mechanism of ECMP, 469–472
    - copper removal rate, 471*f*
    - planarization of a topographic copper layer, 470*f*
    - polarization curves of copper surface, 470*f*
    - novel methods (copper), 462
- Plan-view/cross-sectional SIM images/100-nm thick sputtered Cu, 135*f*
- Plan-view TEM images of 100-nm thick sputtered Cu films, 134*f*
- Plasma-assisted atomic layer deposition (PAALD), 217
- plasma-enhanced ALD (PEALD), 217
- Plasma-enhanced CVD (PECVD), 6, 266
- Plasma process, 279
- Plating and electroless plating, ALD seed layers, 169
- Cu on PA-ALD Pd, electroless deposition, 176–178
    - “end of roadmap” technology, 176
    - FE-SEM images, Cu film on TaNX, 177*f*
    - FE-SEM images, Cu on aspect ratio trench, 177*f*
    - robust native oxide, 176
  - metal ALD process, 170*f*
  - palladium on noble metal, 173–174

- Plating and electroless (*cont.*)  
 hydrogen/argon purge, 173  
 parasitic CVD, 173  
 Pd ALD films, sequential growth, 174*f*  
 palladium on tetrasulfide silane, 174–176  
 higher fluorine level, 174  
 lack of catalytic activity, 174  
 lack of texture, 175  
 quality of film, 174  
 RHEED spectra, Pd ALD films, 175*f*  
 thermal/plasma-enhanced ALD, 171–173  
 Cu precursor thermal decomposition, 173*f*  
 inert hydrogen, 172  
 lack of conformality, 172  
 remote plasma source, 172
- PLC, *see* Programmable logic controllers (PLC)
- P-MOS** transistors, 15
- Poisson's ratio, 288
- Polishing pad, 269
- Poly-arylene-ether (PAE), 278
- Polymer-to-polymer via-last schematic cross section, 86
- Pore-sealing technology, 270, 270*f*
- Porogen, 266
- Porous low-*k* materials, issues, 148
- Porous materials, 258
- Porous methylsilsequioxane (MSQ), 155, 266, 286
- Post-CMP cleaning, 379  
 chemical defects, 380  
 electro-chemical behavior of copper (acid), 383  
 anodic potentiodynamic curves, 383*f*, 384*f*  
 energy dispersive spectroscopy (EDS), 384  
 etching in HNO<sub>3</sub> solution, 381, 382  
 etching process, 382–383  
 exposure in cleaning solutions  
 SEM micrograph, 384*f*  
 interlayer dielectric (ILD) surface, 379  
 mechanical defects, 379–380  
 particle contamination of wafer surface, 379  
 process parameters, 380–382  
 Triton B, 381  
 using distilled water, 381
- Pre-bottom wafer singulation 3D integration, 80
- Pressure cooker test (PCT), 289
- Printed circuit board (PCB), 79
- Pristine elemental surface, 176
- Process optimization/improvement, 285
- Programmable logic controllers (PLC), 218
- Proposed model of air gap, 150*f*
- Prototype air-bridge structures, 153
- Prototype low-profile, high-performance capacitors, 77*f*
- Pseudo-one-dimensional leveling theory model, 240
- Pseudo-wafer 3D integration, 82*f*
- Pulsed cyclic galvanostatic analysis (PGCA), 437, 439
- Pulse plating, 66
- PVD, *see* Physical vapor deposition (PVD)
- Python programming language, 249
- R**
- Raman spectroscopy, 293
- RC delays, 7  
 time, 93
- Reactant diffusion and partial reactions on nanoscale surface, 225*f*
- Reactive ion etching (RIE), 98, 183–186, 276
- Recrystallization of polycrystalline, 82
- “Red Brick Wall,” 275
- Reflection high energy electron diffraction (RHEED), 174
- Reliability parameters, interconnect, 265
- Residual stresses, 153
- Resist ash, 271
- Resistivity changes of 300-nm thick Cu, 139*f*
- Resistivity of Cu lines of various widths, effective, 216*f*
- RHEED, *see* Reflection high energy electron diffraction (RHEED)
- RIE, *see* Reactive ion etching (RIE)
- “Roadmap acceleration,” 25
- Robust process development, 291–293  
 SiV stress test results, 292*f*  
 surrounding pattern effect, mechanism, 292*f*
- S**
- SAM, *see* Self-assembled molecular (SAM)
- SBH, *see* Schottky barrier height (SBH)
- Scalar variable, 246
- Scaling and power dissipation, 29–32  
 direct gate tunneling current density vs. effective oxide thickness, 30*f*  
 guidelines for selecting alternative gate dielectric, 31  
 overview of high-*k* dielectrics, 31*t*
- Scaling theory, 27–29
- Scanning TEM (STEM), 293
- Schottky barrier height (SBH), 122, 128

- Schottky diodes, 110  
 reverse-biased, 110
- Scribing, 148
- “Sea of Kelvin,” 291
- Self-assembled molecular (SAM), 105
- “Self-limiting” behavior, 173
- “Self-sensitizing,” 226
- “Sensitization,” 222  
 methods of ELD, 227*t*–228*t*  
 of nonconductive surfaces, 222
- Shadowing effect, 259, 260
- Short-channel effects, 28
- Signal propagation, 258
- Silane-coupling treatment, 148
- Silicides, 5, 121  
 bulk MPU/ASIC, in ITRS 2005, 123 *f*  
 CoSi<sub>2</sub>, 125  
 contact resistivities, 123 *f*  
 intermetallic compound, 121  
 NiSi, 125–127  
 low consumption of Si, 125  
 low contact resistivity, 126  
 low formation temperature, 125–126  
 low resistivity, 125  
 silicide formation in MOSFET, 122 *f*  
 self-align silicide (salicide) process, 121  
 SiGe incorporation, 127–128  
 energy bandgap, controllability, 127  
 heteroepitaxial growth of Si<sub>1-x</sub>Ge<sub>x</sub>, 127  
 mono-germanosilicide phase, 128  
 realizing higher doping concentrations, 127  
 TiSi<sub>2</sub>, 124–125  
 ULSI application, 121
- Silicide/Si interface, 124
- Silicon-based integrated circuits (ICs), 3
- Silicon-on-insulator (SOI), 34
- Simple EPD cell *vs.* deposition on porous membrane, 74 *f*
- SIMS depth profile of Cu, 109 *f*
- Single-via level model structure, 154 *f*
- Sintering process, 73
- SiOC, *see* Carbon-doped silicon oxide (SiOC)
- SiOC/SiCN films, characteristics, 281*t*
- SiOF, *see* Fluorine-doped silicon oxide (SiOF)
- Si–O ring structures, 269
- SiP, *see* System in a package (SiP)
- SIV, *see* Stress-induced voiding (SiV)
- Small-angle x-ray scattering (SAXS)  
 spectrum, 500–502, 502 *f*
- Small-scale integration (SSI), 3
- S-MAP, *see* Stacked mask process (S-MAP)
- SoC, *see* System-on-chip (SOC) device
- SOD, *see* Spin on dielectric (SOD)
- SOG, *see* Spin on glass (SOG)
- Solution domain and its boundary, 243 *f*
- Source/drain (S/D) contact, 121
- Spin on dielectric (SOD), 145, 266, 285
- Spin on glass (SOG), 145
- Spintronics, nanoscale interconnects  
 technology, 522–524  
 electroplating, 524–526
- Sputtering, 149, 259, 260
- Stacked mask process (S-MAP), 282
- Strained silicon and SOI, 33, 34–35  
 straining silicon channel, 33
- Strained-silicon MOSFETs, 32–34
- Stress-induced voiding (SiV), 265, 279, 291
- Superconformal electrodeposition, modeling  
 adsorption rate, 239  
 Butler–Volmer equation, 240  
 deposition rate, 239, 240  
 Eulerian technique, 241  
 FiPy, 239, 249–252  
 governing equations, 242–245  
 Langmuir adsorption, 244  
 Laplace equation, 240  
 level set equations, 245–246  
 numerical discretization, 247–249
- Superfilling additives, 68
- Surfactants, 65
- Switching Net, 43–45  
 interconnect power, 43–45
- System in a package (SiP), 79  
 three-dimensional integration, 257
- System-on-chip (SOC) device, 257, 275
- T**
- Tafel equation, 240
- Tantalum, plasma clean, 171
- TCAD-Raphael, 156
- TDDB, *see* Time-dependent dielectric  
 breakdown (TDDB)
- “Technology generation”, 93
- TEM, *see* Transmission electron microscopy  
 (TEM)
- TEM/EELS measurements, 294 *f*
- Temperature cycle test (TCT), 289
- Temperature humidity bias (THB), 289
- Tetramethylheptanedionate (tmhd), 171
- Theoretical resistivities/MS model, 132 *f*
- Thermal loading, 153
- Thermal stability, 275
- Thermal stresses, 153
- Thermo-mechanical properties, 153, 164
- Three-dimensional non-volatile memory, 83 *f*

- Through-hole plating, 67  
 Time-dependent dielectric breakdown (TDDB), 265, 293  
 Tobacco mosaic virions, 230*f*  
 Tollens reaction, 221  
 Tomography three-dimensional, 266  
 “Top-down” manufacturing, 4  
 Transfer-printing onto tape, 75  
 Transistors, 28, 40, 211  
   *see also specific transistors*  
 Transmission electron microscopy (TEM), 293  
 Trench air gap, 156  
 TVS measurement of capacitor, 115*f*
- U**  
 ULSI, *see* Ultra large-scale integration (ULSI) technology  
 ULSI metallization/materials/electrical properties, 131–141  
   fabrication technique, 133  
   high-speed ULSI devices/ 70-nm-wide Cu interconnects, 133  
   Mayadas and Shatzkes (MS) model, 131  
   RC delay, 131  
   “self-formation of barrier layer,” 133  
   theoretical resistivity, 132  
 Ultra large-scale integration (ULSI) technology, 3–4, 121, 131, 183–186  
   challenges, ICs, 3–5  
   material issues in Cu interconnects, 5–6  
   performance issues, 7–8  
   process issues, 8–11  
   copper metallization/diffusion barriers, 93–115  
   materials used in manufacturing, interconnects, 6*t*  
     classification, 5  
     performance variables characterize, 7  
 Ultra-low-power consumption, 257  
 “Ultra-shallow junctions,” 17  
 Ultrasonic vibration, 178  
 Ultra violet (UV), 269, 285  
 Unlimited stability, EPD, 74  
 Unsintered Ag–Pd conduction line, 75*f*  
 UV, *see* Ultra violet (UV)
- V**  
 Valence electron energy loss spectroscopy (V-EELS), 293  
 Valence ELS, 294*f*  
 Very large-scale integration (VLSI), 3  
 Void formation, 259  
 Volume-averaged Cu in multi-via level structures  
   trench, 164*f*  
   trench + via air-gap structure, 164*f*  
   trench + via r-gap structure, 164*f*  
 Volume-averaged stresses  
   effective elastic moduli, 165  
   in single-via level structure  
     Cu line stresses, 162*f*  
     Cu via stresses, 162*f*  
   stresses in multi-level structure, 163  
   stresses in single-via structure, 162–163  
 Von Mises stress, 158
- W**  
 Wafer bonding techniques, 84  
 Wafer-level packaging (WLP), 86  
 Wafer process, 157  
 Wafer processing, 257  
 Wagner number, 66  
 Wet chemistry, 177  
 Wide/narrow Cu interconnects/diffusion barrier layer, 132*f*  
 Wiring process, formation of, 149  
 WLP, *see* Wafer-level packaging (WLP)
- X**  
 XPS, *see* X-ray photoelectron spectroscopy (XPS)  
 X-ray fluorescence (XRF), 497–498  
   energy dispersive, 498*f*  
   high-luminosity EDXRF, 498*f*  
 X-ray photoelectron spectroscopy (XPS), 171  
 X-ray reflectometry (XRR), 499–500  
   example of spectrum, 499*f*  
   fast XRR devices, 500  
   simplified scheme, 500*f*  
 X7R capacitor powder, 76*f*
- Y**  
 Young’s modulus, 269, 275
- Z**  
 “Zeta-potential,” 74