

# Integrated Circuit Technology

**2008 Edition**

Written by: Scotten W. Jones

**IC***KNOWLEDGE LLC*

<b>1</b>	<b>Welcome and License</b>	<b>1</b>
1.1	License	1
1.2	About IC Knowledge LLC	2
1.3	IC Knowledge LLC products	2
1.4	Disclaimer	2
1.5	Report outline	3
1.6	What this report is not	3
<b>2</b>	<b>Moore's law: the industry driver</b>	<b>4</b>
2.1	Introduction	4
2.2	Further reading	5
2.3	References	6
<b>3</b>	<b>Introduction to integrated circuit devices</b>	<b>7</b>
3.1	Introduction	7
3.2	Basic electronic concepts	7
3.3	Electronic circuit elements	7
3.4	Atomic structure and band theory	7
3.5	Intrinsic semiconductors	8
3.6	Extrinsic semiconductors	9
3.7	PN junction	10
3.8	Bipolar transistors	11
3.9	MOS capacitor	13
3.10	The MOSFET	15
3.11	MOSFET scaling	17
3.12	NMOS versus PMOS	18
3.13	Conclusion	19
3.14	References	19
<b>4</b>	<b>Integrated circuit manufacturing overview</b>	<b>20</b>
4.1	Silicon wafer manufacturing	20
4.2	Wafer fabrication	22
4.3	Cleanroom technology	29
4.4	Electrical tests	35
4.5	Packaging	38
4.6	References	41
<b>5</b>	<b>Wafer cleaning and photoresist stripping</b>	<b>42</b>
5.1	Surface types	42
5.2	Contaminants	42
5.3	Cleaning chemicals	43
5.4	The RCA clean	44
5.5	IMEC clean	45
5.6	Ohmi Cleans	46
5.7	Evolution of cleaning	46
5.8	Rinsing and drying	46

5.9	Sonic cleaning	49
5.10	Ozone	50
5.11	Backend of line cleaning	52
5.12	Dry cleans	52
5.13	Automation and single wafer cleaning	55
5.14	Photoresist stripping	56
5.15	45nm and 32nm Cleaning and stripping issues	57
5.16	Conclusion	58
5.17	References	58
<b>6</b>	<b>Photolithography</b>	<b>61</b>
6.1	Introduction	61
6.2	Basic photolithography process	61
6.3	Photolithography clusters	70
6.4	Optics	71
6.5	Resolution enhancement	75
6.6	193nm DUV	79
6.7	Immersion lithography	80
6.8	High index immersion	83
6.9	Double patterning	85
6.10	Extreme ultraviolet (EUV)	86
6.11	Conclusion	88
6.12	References	88
<b>7</b>	<b>Etching</b>	<b>91</b>
7.1	Introduction	91
7.2	Basic etch concepts	91
7.3	Wet versus dry etching	92
7.4	Etching requirements	92
7.5	Plasmas	92
7.6	Basic plasma chemistry	95
7.7	Chemical versus ion etching	98
7.8	Plasma etching systems	98
7.9	High density plasma etch systems	100
7.10	Etch processes	101
7.11	45nm and 32nm etching challenges	103
7.12	Conclusion	103
7.13	References	104
<b>8</b>	<b>Ion Implantation and Annealing</b>	<b>106</b>
8.1	Introduction	106
8.2	Ion-solid interactions	106
8.3	Ion implanter system basics	113
8.4	Types of ion implanters	120
8.5	Applications	124
8.6	Annealing	126
8.7	Rapid Thermal Processing (RTP) theory	127

8.8	Junction formation requirements for sub-65nm junctions	130
8.9	Conclusion	132
8.10	References	133
<b>9</b>	<b>Dielectric Deposition</b>	<b>134</b>
9.1	Introduction	134
9.2	Basic concepts	134
9.3	Dielectric deposition systems	139
9.4	Applications	144
9.5	References	146
<b>10</b>	<b>Metallization</b>	<b>148</b>
10.1	Introduction	148
10.2	Basic principles	148
10.3	Metallization systems	160
10.4	Applications	163
10.5	References	164
<b>11</b>	<b>Chemical Mechanical Planarization (CMP)</b>	<b>166</b>
11.1	Introduction	166
11.2	Basic concepts	166
11.3	CMP systems	169
11.4	CMP applications	172
11.5	Post CMP cleaning	173
11.6	Current challenges	174
11.7	Electro Chemical Mechanical Planarization (ECMP)	175
11.8	Conclusion	176
11.9	References	176
<b>12</b>	<b>CMOS process integration</b>	<b>177</b>
12.1	The invention of CMOS	177
12.2	Isolation	178
12.3	Wells	181
12.4	Transistor formation	184
12.5	Contacts	194
12.6	Interconnect	195
12.7	Passivation	205
12.8	Conclusion	205
12.9	References	205
<b>13</b>	<b>CMOS technology trends</b>	<b>207</b>
13.1	Die size	207
13.2	Linewidth and scaling trends	208
13.3	Process complexity trends	210
13.4	Operating frequency	211

13.5	Interconnect	211
13.6	Drive current	214
13.7	Operating voltage	214
13.8	Gate oxide thickness	214
13.9	Power dissipation	216
13.10	Design rule trends	217
13.11	References	218
<b>14</b>	<b>45nm CMOS logic process flow</b>	<b>220</b>
14.1	Major process blocks	220
14.2	Epitaxial substrate	221
14.3	Shallow trench isolation	221
14.4	Wells and threshold adjust	223
14.5	Gate formation	225
14.6	Drain extensions and halo	227
14.7	Spacers and embedded silicon germanium formation	229
14.8	Source-drain and ILD0	231
14.9	Dual metal gate formation	233
14.10	Contact, local interconnect and silicide	235
14.11	Plugs and metal 1	237
14.12	Metal 2	239
14.13	Metal 3+	241
14.14	Passivation	241
14.15	References	241
<b>15</b>	<b>32nm CMOS logic processes</b>	<b>242</b>
15.1	Introduction	242
15.2	32nm logic process overview	242
15.3	Metal gates	242
15.4	Conclusion	246
15.5	References	247
<b>16</b>	<b>Sub 32nm devices</b>	<b>248</b>
16.1	Gate oxide leakage	248
16.2	Off-state leakage	248
16.3	Fully depleted SOI	248
16.4	Conclusion	253
16.5	References	253
<b>17</b>	<b>DRAM Technology</b>	<b>255</b>
17.1	Introduction	255
17.2	Memory cell	255
17.3	DRAM architecture	255
17.4	Capacitor scaling	256
17.5	Access transistor scaling	258
17.6	Trench DRAM fabrication	258

17.7	Stacked capacitor	265
17.8	Summary	276
17.9	References	276
<b>18</b>	<b>Flash Memory Technology</b>	<b>279</b>
18.1	Introduction	279
18.2	Floating gate operation	279
18.3	Multibit Flash	280
18.4	NAND and NOR Flash architectures	280
18.5	NAND Flash process	280
18.6	NOR Flash process	286
18.7	Flash scaling issues	289
18.8	References	290
<b>19</b>	<b>Silicon Germanium</b>	<b>292</b>
19.1	Introduction	292
19.2	History of silicon germanium	292
19.3	Silicon germanium integration	293
19.4	References	295
<b>20</b>	<b>Substrates</b>	<b>296</b>
20.1	Introduction	296
20.2	Bulk substrates	296
20.3	Epitaxial substrates	298
20.4	Silicon-On-Insulator substrates (SOI)	299
20.5	Strained silicon	303
20.6	Conclusion	307
20.7	References	307
<b>21</b>	<b>Low-k dielectrics</b>	<b>310</b>
21.1	Introduction	310
21.2	Low-k dielectric material requirements	310
21.3	What determines k	310
21.4	Low-k films	312
21.5	Conclusion	315
21.6	References	316
<b>22</b>	<b>High-k dielectrics</b>	<b>319</b>
22.1	Introduction	319
22.2	High-k materials for DRAM capacitor	319
22.3	High-k materials for gate dielectrics	320
22.4	Conclusion	323
22.5	References	324

## 1.0. Welcome and License

Welcome to the IC Knowledge LLC - 2008 Integrated Circuit Technology Report. We would like to thank you for choosing IC Knowledge LLC. We believe the IC Technology Report you have purchased is the most comprehensive, accurate and up-to-date IC Technology information available. This report is designed to be self explanatory, but if you have a question we will answer a reasonable number of e-mails for 12 months after the purchase date. Our e-mail address is info@icknowledge.com. We hope you find our report interesting and that it meets your needs.

### 1.1. License

**IMPORTANT-READ CAREFULLY:** This License agreement (“LICENSE”) is a legal agreement between you (“INDIVIDUAL”) and IC Knowledge LLC. By installing, copying or otherwise using the IC Technology report (“REPORT”), you agree to be bound by the terms of this LICENSE.

The REPORT is protected by copyright laws and international copyright treaties, as well as other intellectual property laws and treaties. The REPORT is licensed, not sold.

#### 1.1.1. DEFINITIONS

- LICENSE - a legal agreement covering the allowable use of the REPORT.
- REPORT - the IC Knowledge LLC - 2008 IC Technology report comprised of an Adobe Acrobat file containing text, figures and tables.
- INDIVIDUAL - the person that purchases the REPORT and is licensed to use the REPORT.
- COMPANY - a company employing the Individual at the time the Individual purchases the REPORT.

#### 1.1.2. LICENSE: This LICENSE grants the INDIVIDUAL the following rights.

- The INDIVIDUAL may save a single copy of the REPORT on a private local hard drive or private directory on a network hard drive.
- The INDIVIDUAL may make a single copy of the REPORT as may reasonably be required for backup.
- The INDIVIDUAL may make use of the information contained in the REPORT in the preparation of reports and analysis used to further the interests of the COMPANY or INDIVIDUAL.
- The INDIVIDUAL may make limited use of the information contained in the REPORT for the preparation and delivery of presentations provided such information is clearly identified as being copyright IC Knowledge LLC all rights reserved.

#### 1.1.3. LIMITATIONS: The following rights are explicitly excluded.

- The INDIVIDUAL may not at any time save the REPORT on any medium where multiple people have access to the location where the file is stored.
- The INDIVIDUAL may not resell, rent or redistribute the REPORT.
- The INDIVIDUAL may not use the REPORT to provide information for multiple third parties.

#### 1.1.4. COPYRIGHT

All title and copyrights in and to the REPORT (including but not limited to any images, photographs, animations, video, audio, music, text and “applets,” incorporated into the REPORT), any copies of the REPORT, are owned by IC Knowledge LLC. IC Knowledge LLC reserves all rights not specifically granted under this License.

#### 1.1.5. PROPRIETARY DATA

The INDIVIDUAL agrees not to make any attempts to “hack” or guess the password used by IC Knowledge LLC to protect the REPORT from page and or figure extraction and editing.

#### 1.1.6. UPDATES

Included in the price of the REPORT is any and all updates made to the 2007 REPORT. Such updates may or may not be generated at the sole discretion of IC Knowledge LLC.

### **1.1.7. ASSIGNMENT**

- The INDIVIDUAL may be changed at any time to any employee of the COMPANY by notifying IC Knowledge LLC by e-mail of the change. E-mail notification should be sent to info@icknowledge.com.
- In the event that the COMPANY is acquired by another Company, the acquiring company will become the COMPANY under this agreement once IC Knowledge LLC has been notified by e-mail of the change. E-mail notification should be sent to info@icknowledge.com.

### **1.1.8. NON-WAIVER**

- No failure of IC Knowledge LLC to strictly enforce any term, right or condition of this LICENSE shall be construed as a waiver of such term, right or condition for the purpose of any subsequent occasion or event.

### **1.1.9. CHOICE OF LAW; JURISDICTION**

- This LICENSE shall be interpreted and governed by the laws of the state of Massachusetts.

### **1.1.10. VALIDITY**

- If any term or provision of this LICENSE shall be determined to be invalid or unenforceable under applicable law, such provision shall be deemed severed from this LICENSE, and the remaining provisions of this Agreement shall remain in full force and effect.

### **1.1.11. TERMINATION**

- Without prejudice to any other rights, IC Knowledge LLC may terminate this LICENSE if the INDIVIDUAL fails to comply with the terms and conditions of this LICENSE. In such event, the INDIVIDUAL must destroy all copies of the REPORT.

## **1.2. About IC Knowledge LLC**

IC Knowledge LLC was founded in the year 2000 by a group of wafer fabrication technologists and management specialists. IC Knowledge LLC is dedicated to offering the finest training and reference materials available to the semiconductor industry.

## **1.3. IC Knowledge LLC products**

- Integrated Circuit Cost Model - a Microsoft Excel based cost model that uses dropdown menu selections to generate product costs for most integrated circuit products.
- MEMS Cost Model - a Microsoft Excel based cost model that uses dropdown menu selections to generate product costs for most MEMS products.
- Integrated Circuit Economics - a report covering the economics of the integrated circuit industry.
- Integrated Circuit Packaging - a report covering the packaging market, packaging technology, test, packaging technology trends, packaging foundry selection and pricing.
- Integrated Circuit Technology - this report.
- 300mm Watch - a database of 300mm fabs and companion analysis.
- Cleanroom Reference Guide for Semiconductor and MEMS Applications - a concise reference guide containing all the information needed to design, build and operate a cleanroom.
- A Visual Guide to Semiconductor Process Equipment - a highly visual guide describing the theory, operation and usage of the major types of semiconductor process equipment.

## **1.4. Disclaimer**

We believe the information presented in this publication to be accurate and representative of general integrated circuit industry practices. Much of the information in this report is compiled from technical journals and other secondary sources. IC Knowledge LLC does not warranty the accuracy of the information presented in this report in any way. It is up to the user to determine whether the information presented is applicable to the situation the user is interested in.

## 1.5. Report outline

This report is broken up into 22 chapters:

- Chapter 1 - Welcome
- Chapter 2 - Moore's law: the industry driver
- Chapter 3 - Introduction to integrated circuit devices
- Chapter 4 - Integrated circuit manufacturing overview
- Chapter 5 - Wafer cleaning and photoresist stripping
- Chapter 6 - Photolithography
- Chapter 7 - Etching
- Chapter 8 - Ion Implantation and annealing
- Chapter 9 - Dielectric deposition
- Chapter 10 - Metallization
- Chapter 11 - Chemical mechanical planarization
- Chapter 12 - CMOS process integration
- Chapter 13 - CMOS technology trends
- Chapter 14 - 45nm CMOS logic process flow
- Chapter 15 - 32nm CMOS logic processes
- Chapter 16 - Sub 32nm devices
- Chapter 17 - DRAM Technology
- Chapter 18 - Flash Memory Technology
- Chapter 19 - Silicon Germanium
- Chapter 20 - Substrates
- Chapter 21 - Low-k dielectric
- Chapter 22 - High-k dielectric

## 1.6. What this report is not

This report is meant to give the reader an understanding of integrated circuit technology and technology trends.

- We discuss general market trends, but this is not a market research firm and we are not in the business of forecasting the market. For market research and forecasts we recommend IC Insights at [www.icinsights.com](http://www.icinsights.com).
- This report presents some discussion of the economics of the technologies presented, but for a detailed discussion of integrated circuit economics we recommend our IC Economics report.
- This report presents a very brief discussion of packaging, for a more detailed discussion of packaging we recommend our packaging report.
- This report includes descriptions of the operation of many pieces of semiconductor process equipment. For a more detailed discussion of semiconductor process equipment we recommend our Visual Guide to Semiconductor Process Equipment.