

## Table of Contents

### Contents

<b>Table of Contents</b>	4
<b>List of Figures</b>	9
<b>1. Executive Summary</b>	11
1.1. Supply-Chain Challenges	11
<b>2. Scope</b>	11
<b>3. Introduction</b>	12
3.1. The Start and Growth of the Semiconductor Industry	14
3.2. The Asian Semiconductor Industry	19
3.3. The Changing Market	20
3.4. Where have we come from?	22
<b>4. Future Trends</b>	23
4.1. Economics	23
4.2. MegaFabs and Gigafabs	26
4.3. Inflection Points	30
4.4. TECHCET's Wafer Forecast Model	31
<b>5. Device Technologies</b>	36
5.1.1. LOGIC	37
5.1.2. Memory	41
5.1.3. NON-VOLATILE MEMORY	42
5.1.4. 3D NAND	43
5.1.5. STORAGE CLASS MEMORY DEVICES	46
5.1.5.1. 3D XPoint	46
5.2. New Device Structures	47
5.2.1. Memory Structures	47
5.2.2. Logic Structures	48
5.3. New Memory	52
5.3.1. RRAM or ReRAM	52
5.3.2. STT-RAM	53
5.3.3. PCRAM	55
5.3.4. FeRAM	57

5.4.	Limited or Research stage	58
5.4.1.	MVO	58
5.4.2.	CBRAM	60
5.4.3.	NRAM	61
5.4.4.	Molecular/Carbon	62
5.4.5.	Transistors For CMOS Extensions (ITRS 2015)	63
5.4.5.1.	Carbon Nanotube FETs	63
5.4.5.2.	Nanowire FETs	63
5.4.6.	III-V Channel Replacement Devices	64
5.5.	IoT Impacts	66
6.	Device to Process to Material	70
6.1.	3D NAND Process Challenge	70
6.2.	New Materials used in Memory	73
6.2.	Device Formation	74
6.3.	Interconnect	77
6.4.	Lithography	83
6.5.	ALD	88
6.6.	ALE – Atomic Layer Etching	90
6.7.	Cleaning	92
6.8.	Materials	94
6.8.1.	ALD/CVD PRECURSORS	94
6.8.2.	Device Formation	94
6.8.3.	Interconnect	95
6.8.4.	Market Environment	95
6.8.5.	Gases	96
6.8.6.	Inert Gases	98
6.8.7.	Bulk Chemicals	99
6.8.8.	Dielectrics Precursors	100
6.9.	CMP	103
6.10.	Sputtering Targets	103
6.11.	Photoresists, Ancillaries & Extension Materials	105
7.	Process Materials Concerns & Issues	107
7.11.	Materials Supply Chain Management	107
7.12.	Quality and Purity Issues	107

<b>7.13. Materials Supply Chain Issues</b>	110
<b>7.14. Future Materials Requirements and Rare Earths Minerals and Metals</b>	111
<b>8. Changes in the Materials Market Opportunities</b>	112
<b>8.1. IoT opportunities</b>	112
<b>9. Global and Operation issues</b>	112
<b>9.1. Recycling</b>	112
<b>9.2. Cost Structure Changes</b>	113
<b>9.3. WIP Management</b>	115
<b>9.4. Semiconductor Center of Gravity Shifts West</b>	115
<b>9.5. Meeting the China Challenges</b>	118
<b>11. Conclusions &amp; Take Aways</b>	122
<b>12. Bibliography</b>	124
<b>13. TECHCET Critical Materials Report Advisories</b>	125

## List of Figures

- Figure 1 Shockley Laboratory – where the semiconductor industry began
- Figure 2 Silicon Valley Genealogy
- Figure 3 Japanese Yen to US Dollar Exchange Rates from 1976 to 2016
- Figure 4 Hsinchu Science Park
- Figure 5 Elements used in today's smartphones
- Figure 6 Depletion of elements – how long will the supply of certain elements last?
- Figure 7 TSMC Wafer Revenue from Advance Process Technology 22
- Figure 8 TSMC Cell Cost Trends
- Figure 9 Companies building major Fabs and growth in Fab CAPEX and process development costs.
- Figure 10 Capex for Top 10 Semiconductor Companies - Revenue
- Figure 11 High purity semiconductor utility systems – Training Opportunity
- Figure 12 TECHCET's Wafer Forecast Model
- Figure 13 Emerging Memory Devices
- Figure 14 Memory Scaling Wall
- Figure 15 IMEC Logic Roadmap
- Figure 16 Transistor Revolution (AMAT Inflection Point Presentations)
- Figure 17 Key Inflections in Moore's Law (AMAT Inflection Presentation) DRAM
- Figure 18 Advantages of Vertical MOSFETs
- Figure 19 V-NAND TEM showing levels
- Figure 20 V-NAND showing gate detail (AMAT)
- Figure 21 V-NAND showing stair-step interconnect structure (Techinsights)
- Figure 23 What is 3D XPoint?
- Figure 24 Recessed Channel Transistors
- Figure 25 Replacement Gate Transistor Stacking
- Figure 26 LETI CoolCube

Figure 27 Heat map  
Figure 28 Which Materials are Manufacturing Worthy?  
Figure 29 HfOx Based RRAM  
Figure 30 STT-RAM Structure  
Figure 31 Complex Structure for STT-RAM (ITRS)  
Figure 32 Phase Change Materials  
Figure 33 Chalcogenide Phase Change Memory  
Figure 34 FeRAM Material  
Figure 35 FRAM  
Figure 36 Alternative Memory Concepts (Micron)  
Figure 37 CBRAM showing states  
Figure 38 Re-RAM Dual CbRAM  
Figure 39 NRAM or Nano RAM  
Figure 40 Molecular Memory Device  
Figure 41 Flow of 200mm tools to China  
Figure 42 IoT growth (ITRS and INEMI Public 2016)  
Figure 43 200mm Fab count since 2007 (TEHCET)  
Figure 44 ASPs of 200mm tools purchased by fabs in China (Global Surplus)  
Figure 45 IoT semiconductor market by market sector (IBS 2015)  
Figure 46 It's Elemental(Micron)  
Figure 47 Logic Cross Section (AMAT/Techinsight)  
Figure 48 ITRS Half-pitch Conversion (ITRS)  
Figure 50 Mask by Node (TEHCET)  
Figure 51 EUV Schematic indicating the complexity  
Figure 52 Masks per Mask Set (eBeam Initiative)  
Figure 53 Market Share of ASML, Canon and Nikon  
Figure 54 ALD Materials Innovations  
Figure 55 ALE Cycles  
Figure 56 ALE and ALD steps  
Figure 57 Neon Supply Matrix  
Figure 58 Gases as a percentage of Air  
Figure 59 Control Charts  
Figure 60 Material Supply Problems  
Figure 61 Technology Roadmap for IoT  
Figure 62 Parameters by NODE

## List of Tables

Table 1 Progress over 4 Decades

Table 2 Cost Analysis Table

Table 3 ITRS Logic Roadmap (2015)

Table 4 DRAM Technology

Table 5 NAND Flash

Table 6 Devices and Materials

Table 7 Interconnect levels Logic/Memory(IMEC)

Table 9 Scaling Trend - ALD Applications for Memory & Logic

Table 7 Upcoming Chinese Fabs