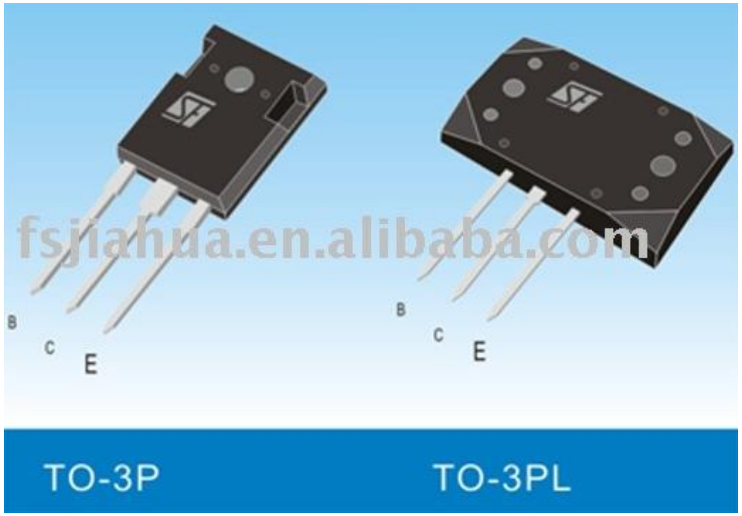
Chapter 6

Semiconductor Processing: Moore's Law

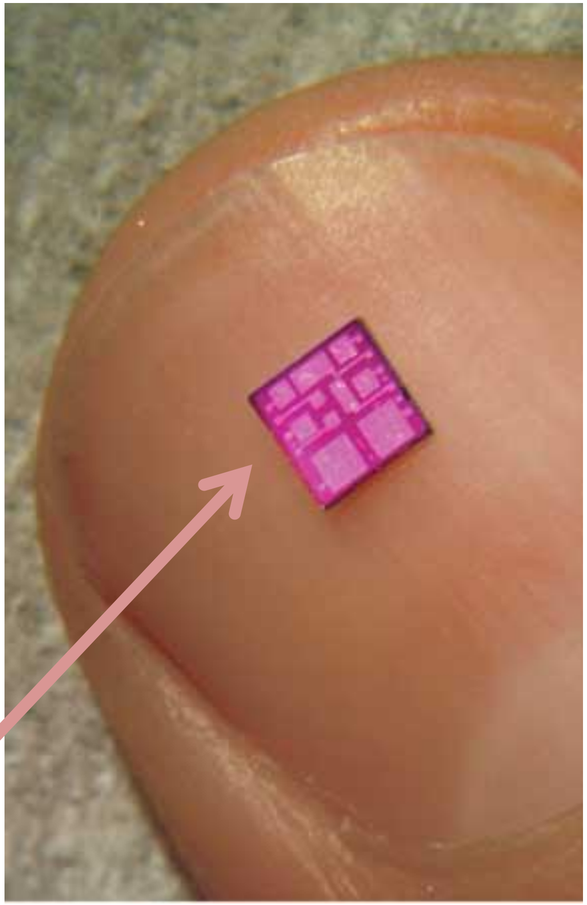
Semiconductor Processing & Fabrication

- Semiconductors are very interesting and versatile materials from an engineering point of view. As we have seen, through doping, their electrical properties can be varied over an enormous range in a controlled way
- Furthermore, by arranging regions of the doped crystal with adjacent P-type and N-type regions many new effects are produced which can be used to produce diodes, transistors and other devices (more later)
- While individual or discrete devices are useful, the real power of semiconductor technology comes when the transistors and many other components (resistors, capacitors, wires or 'interconnects') are all fabricated simultaneously in a single small Integrated Circuit (IC) or Silicon 'chip'.

Semiconductor Products



Discrete (Packaged) Bipolar Transistors



Integrated Circuit
1,000,000's++ of transistors

Integrated Circuits (ICs)

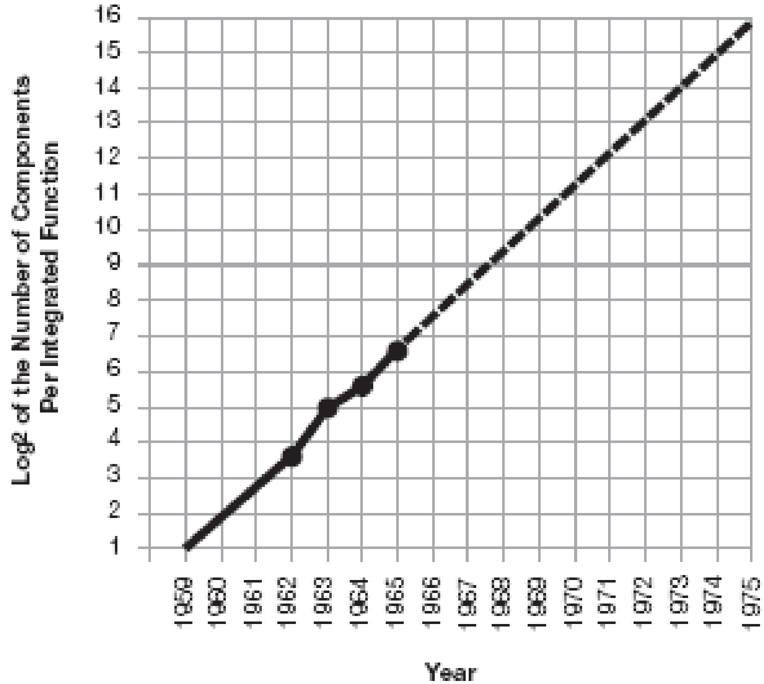
- Over 95% of the semiconductor products now being produced are ICs, each one of which is in the form of a thin rectangular chip with a surface area typically of the order of $1cm^2$
- Many hundreds of ICs are cut from a single circular wafer of semiconductor, with all the complex patterning being performed on one side. In practice, multiple wafers are processed simultaneously in a semiconductor fabrication plant or 'fab'. This kind of multiple or 'batch' production greatly reduces the costs of production
- The technology associated with the complex patterning is called lithography and a critical metric is the minimum feature size that can be reliably patterned on the surface: the smaller this is, the more components can be packed into an IC

A Short History...

- The first experiments with semiconductors were conducted by Ferdinand Braun in the 1870's, but no applications could be seen at that time
- The early decades of electronics were dominated by valve or tube devices using focussed electron beams in evacuated glass tubes passing through meshes between 'plates'
- In a drive to produce smaller and more reliable devices, Bardeen, Brittain and Shockley working at Bell Labs in NJ, USA developed the semiconductor (bipolar) 'transistor' in 1947.
- An engineer named Jack Kilby working for Texas Instruments proposed the Integrated Circuit in 1957
- In 1965, Gordon Moore of Intel wrote a famous paper...

Moore's Law

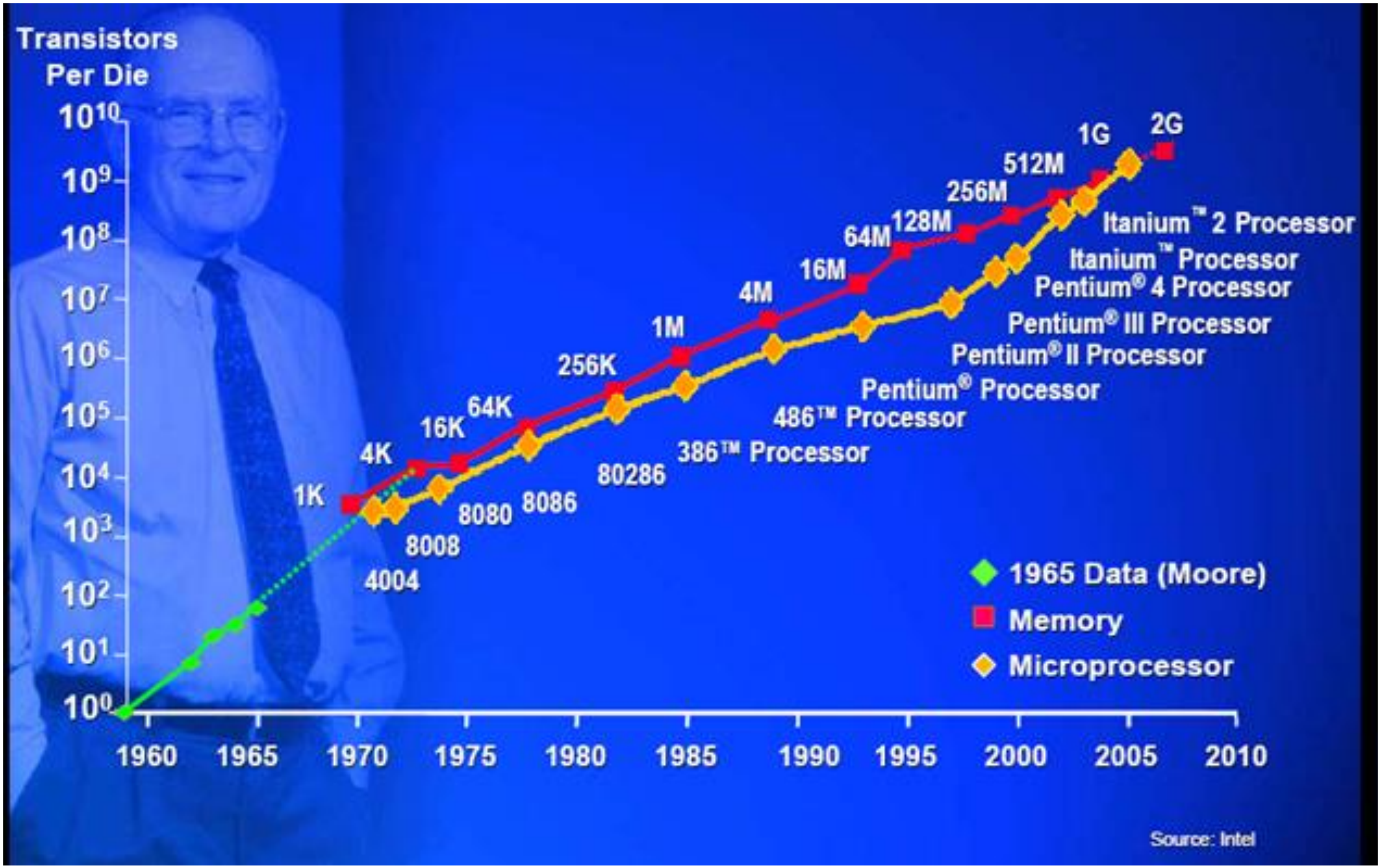
- Moore observed (based on very few data points) that progress in lithography seemed to indicate an approximate doubling of the density of components on an IC about every 12months
- He extrapolated this trend forward just to 1975, but remarkably his prediction of exponential growth in IC complexity has so far held good for 50 years!
- The long-term time interval of doubling has been more consistently around 18mths – 2years

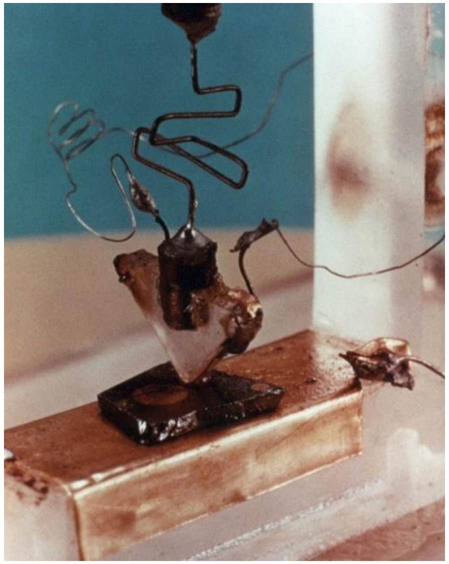


From Moore's original 1965 paper

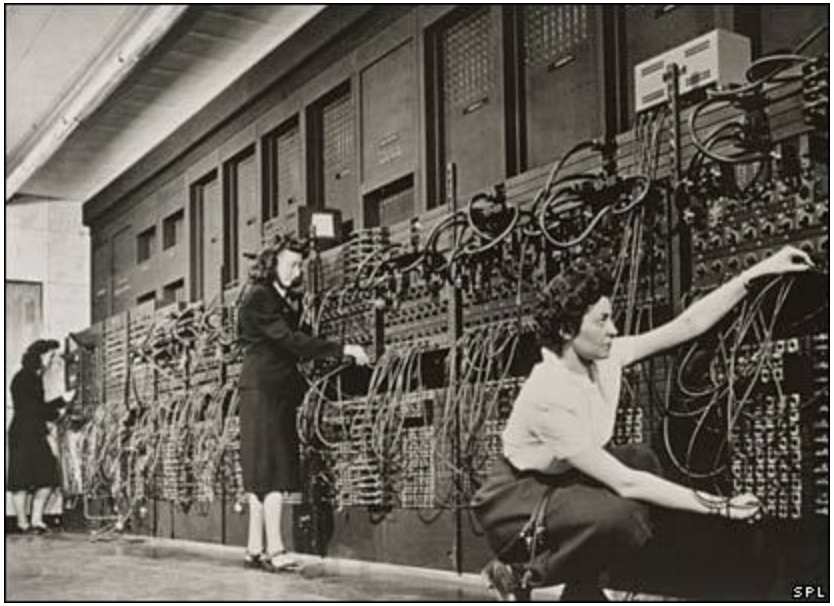
See full paper on Blackboard

Moore's Law: Still Going Strong into the 21st Century...

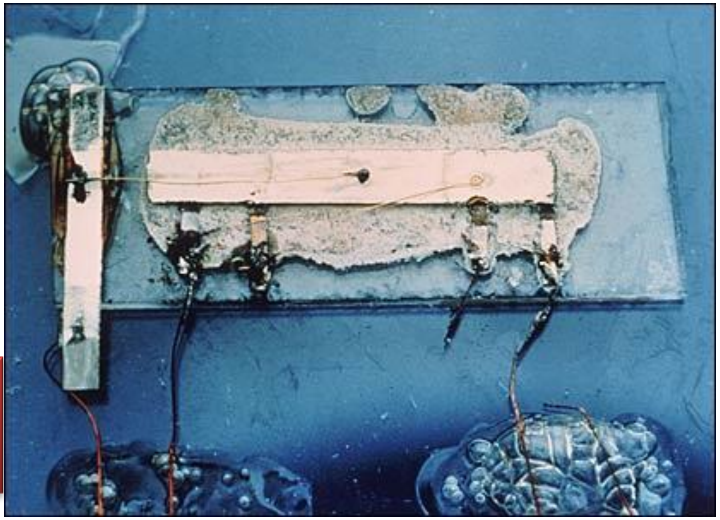




First Transistor (1947)



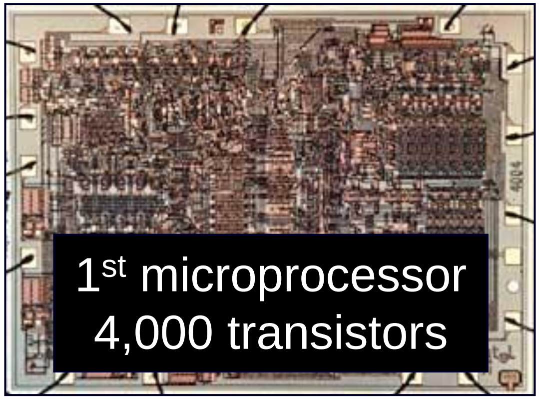
Early Valve-Based Computer (1940)



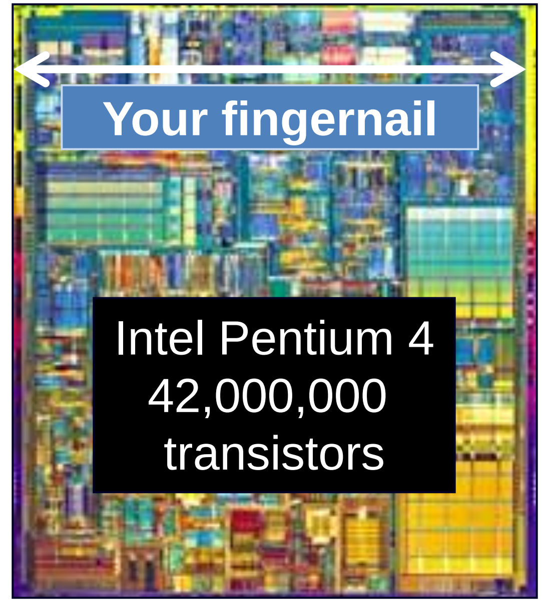
Kilby's First Integrated Circuit (1957)

The Enormous Pace of IC Progress…

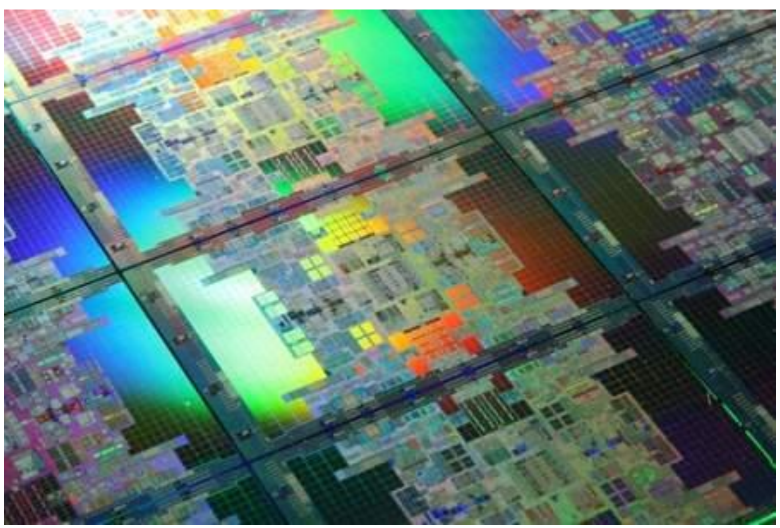
1970



2000



2010



Intel Itanium processor
≈2 Billion transistors/chip

On August 7, 2014, IBM announced their second generation SyNAPTIC chip, which contains the most transistors in a Neurosynaptic chip to date at 5.4 billion.

Early UCD EE Involvement in Intel

The beginnings of Intel in 1968.

* Desmond FitzGerald
B.E. Graduate in Electrical Engineering, UCD, 1958

Moore’s Law: How Long Will it Continue...?

- It is difficult to overstate the importance of and impact of Moore’s law over the past 50 years – without this exponential increase in the functionality of ICs (and corresponding exponential decrease in the cost per function) much of our modern world would simply not exist: no smartphones, no Internet, no laptops, no PS3s, no ipads...
- A critical question is how long more will Moore’s Law continue. The end has been (falsely) predicted many times and there is no absolute certainty, but there are good grounds for believing that at least another 10 years of exponential growth along Moore’s original trajectory will take place

Semiconductor Business Models

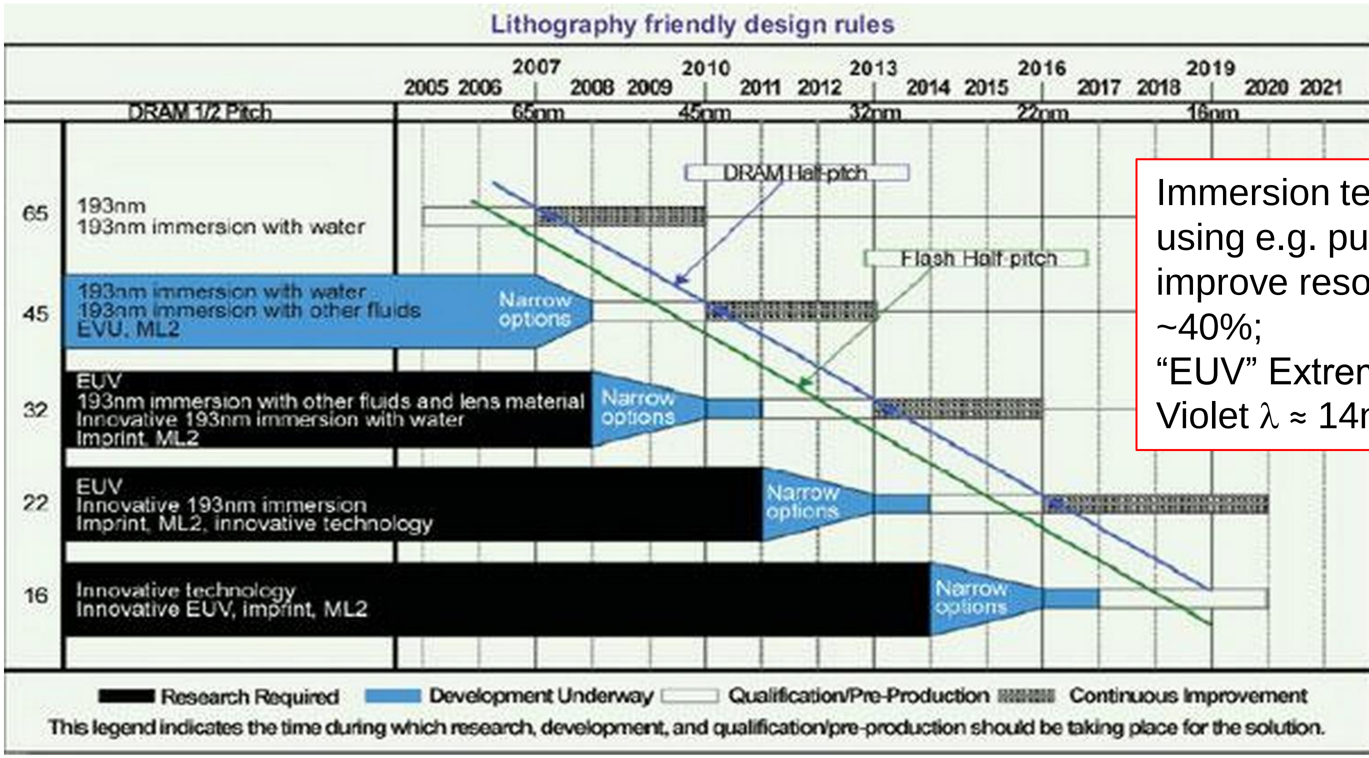
- ICs are made in advanced manufacturing plants called "fabs";
- Some vendors of ICs both design and fabricate their own chips in-house – they are sometimes called "Integrated Device Manufacturers" or IDMs (e.g. Intel or AMD);
- In many other case the design company may be quite separate from the manufacturer. In this case "fabless design houses" concentrate on the design and IP (intellectual property) aspects, while contracting out the actual production to merchant "foundries" (if these just do outside work they are called "pure play"). A major example of a foundry of this kind is the Taiwan Semiconductor Manufacturing Co. (TSMC);
- There are several fabless IC design companies in Ireland (e.g. S3, DecaWave, Movidius etc – see later).

‘Nodes’ in Lithography

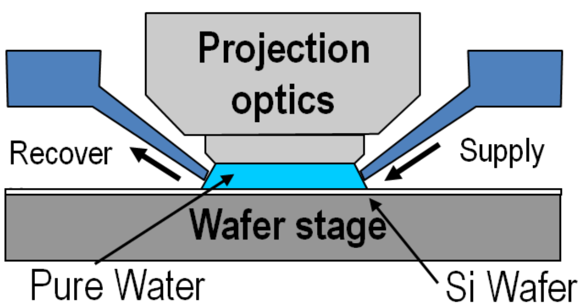
- The march of Moore’s law is measured in discrete increments called technology nodes corresponding to the minimum feature size achievable. The schedule for this is set out by the International Technology Roadmap for Semiconductors (“ITRS Roadmap”)[1];
- At present, the 22nm node is in production in advanced fabs. Preparations for the next 14nm node are already underway (~70% smaller - i.e. a doubling of complexity per unit area). Beyond that is the 10nm node etc.
- Each node raises increasingly severe technical challenges to be overcome, some to do with material uniformity, others to do with lithography and others due to fundamental limits on device behaviour. One future solution may be 3D ICs...
- A major fab for each node is a colossal capital investment (e.g. Intel Arizona €4B 2012 or TMSC in Taiwan €6B in 2013, which then depreciates very rapidly!

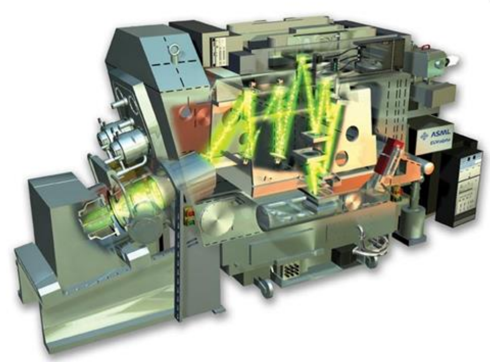
[1] *http://www.itrs.net/Links/2013ITRS/Summary2013.htm*

ITRS Lithography



Immersion techniques using e.g. pure water improve resolution by ~40%;
“EUV” Extreme Ultra-Violet λ ≈ 14nm



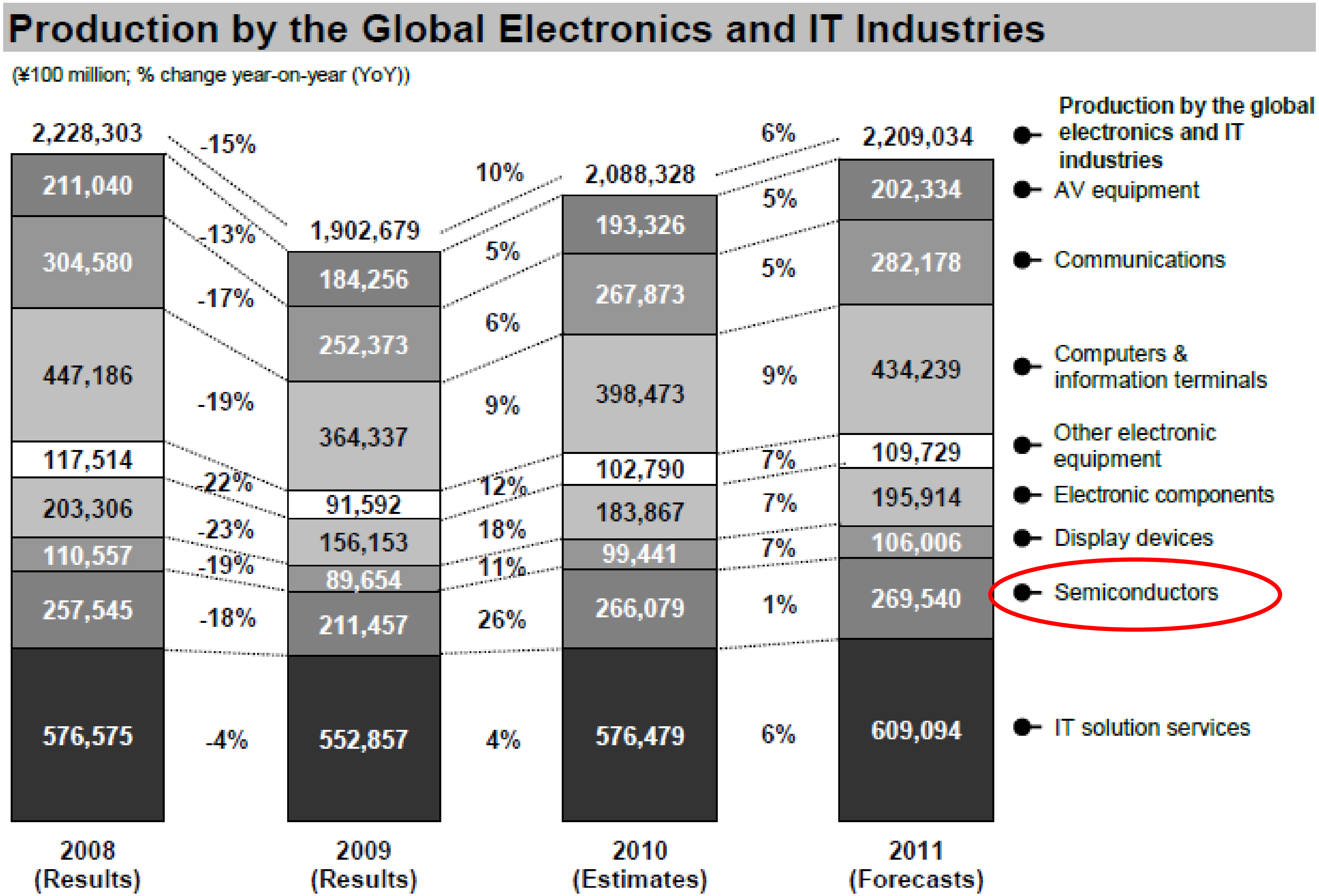


2013 ITRS Roadmap Summary

Table ORTC1 Summary Table of ITRS Technology Trend Targets

Year of Production	2013	2015	2017	2019	2021	2023	2025	2028
Logic Industry "Node Name" Label	"16/14"	"10"	"7"	"5"	"3.5"	"2.5"	"1.8"	
Logic ½ Pitch (nm)	40	32	25	20	16	13	10	7
Flash ½ Pitch [2D] (nm)	18	15	13	11	9	8	8	8
DRAM ½ Pitch (nm)	28	24	20	17	14	12	10	7.7
FinFET Fin Half-pitch (new) (nm)	30	24	19	15	12	9.5	7.5	5.3
FinFET Fin Width (new) (nm)	7.6	7.2	6.8	6.4	6.1	5.7	5.4	5.0
6-t SRAM Cell Size(um2) [@60f2]	0.096	0.061	0.038	0.024	0.015	0.010	0.0060	0.0030
MPU/ASIC HighPerf 4t NAND Gate Size(um2)	0.248	0.157	0.099	0.062	0.039	0.025	0.018	0.009
4-input NAND Gate Density (Kgates/mm) [@155f2]	4.03E+03	6.37E+03	1.01E+04	1.61E+04	2.55E+04	4.05E+04	6.42E+04	1.28E+05
Flash Generations Label (bits per chip) (SLC/MLC)	64G /128G	128G /256G	256G / 512G	512G / 1T	512G / 1T	1T / 2T	2T / 4T	4T / 8T
Flash 3D Number of Layer targets (at relaxed Poly half pitch)	16-32	16-32	16-32	32-64	48-96	64-128	96-192	192-384
Flash 3D Layer half-pitch targets (nm)	64nm	54nm	45nm	30nm	28nm	27nm	25nm	22nm
DRAM Generations Label (bits per chip)	4G	8G	8G	16G	32G	32G	32G	32G
450mm Production High Volume Manufacturing Begins (100Kwspm)				2018				
Vdd (High Performance, high Vdd transistors)[**]	0.86	0.83	0.80	0.77	0.74	0.71	0.68	0.64
1/(CV/I) (1/psec) [**]	1.13	1.53	1.75	1.97	2.10	2.29	2.52	3.17
On-chip local clock MPU HP [at 4% CAGR]	5.50	5.95	6.44	6.96	7.53	8.14	8.8	9.9
Maximum number wiring levels [unchanged	13	13	14	14	15	15	16	17
MPU High-Performance (HP) Printed Gate Length (GLpr) (nm) [**]	28	22	18	14	11	9	7	5
MPU High-Performance Physical Gate Length (GLph) (nm) [**]	20	17	14	12	10	8	7	5
ASIC/Low Standby Power (LP) Physical Gate Length (nm) (GLph)[**]	23	19	16	13	11	9	8	6

Semiconductors (ICs) Leverage a Multi-Trillion€ Global Electronics Business:



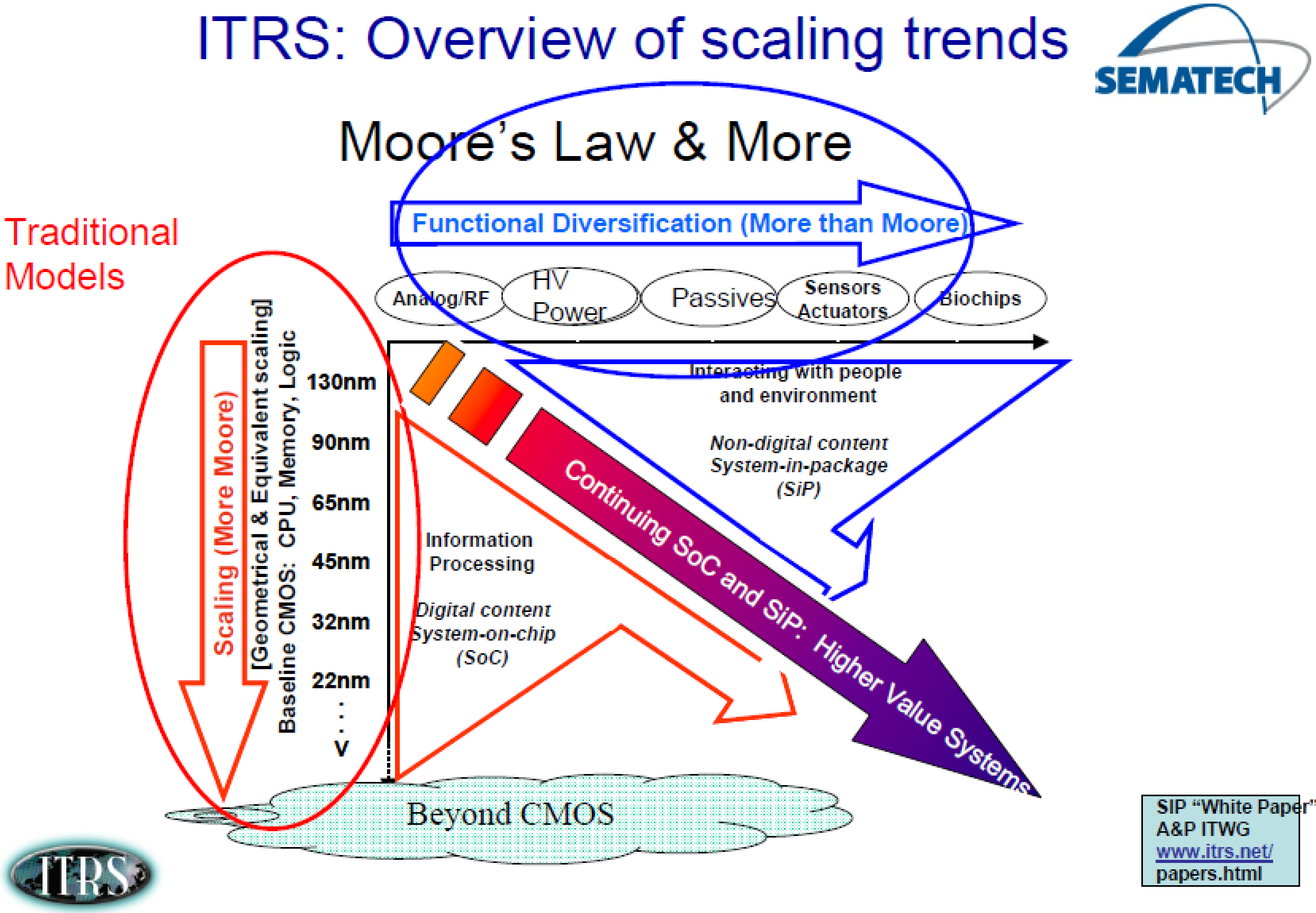
Projected Global Semiconductor Industry Growth

More Moore… or More Than Moore?

- Two broad trajectories are often identified for the future evolution of IC technology:
  - More Moore, meaning a continuation of the standard ITRS road map with aggressive CMOS scaling. This is challenged by atomic scale dimensions, the physical limits of device operation, severe problems with process variability, high power dissipation, a tendency towards diminishing returns..
  - More Than Moore, encompassing heterogeneous technologies combined as a System on a Chip (SoC) or System in a Package (SiP). The technologies could include RF, analogue, MEMS* (or NEMS), sensors, power components, optoelectronics..

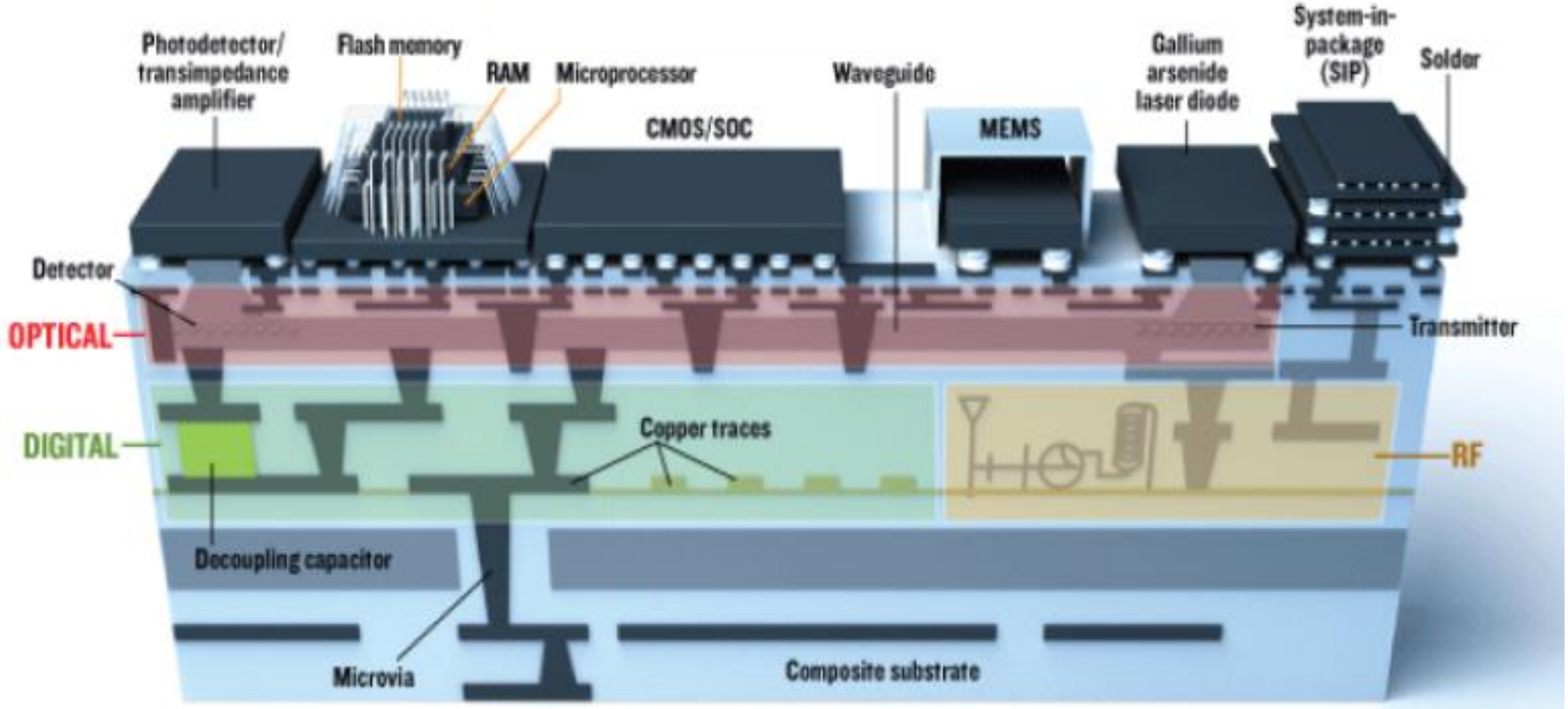
** Micro (or Nano) Electronic Mechanical Systems*

ITRS: Overview of scaling trends



SIP "White Paper"
A&P ITWG
www.itrs.net/
papers.html

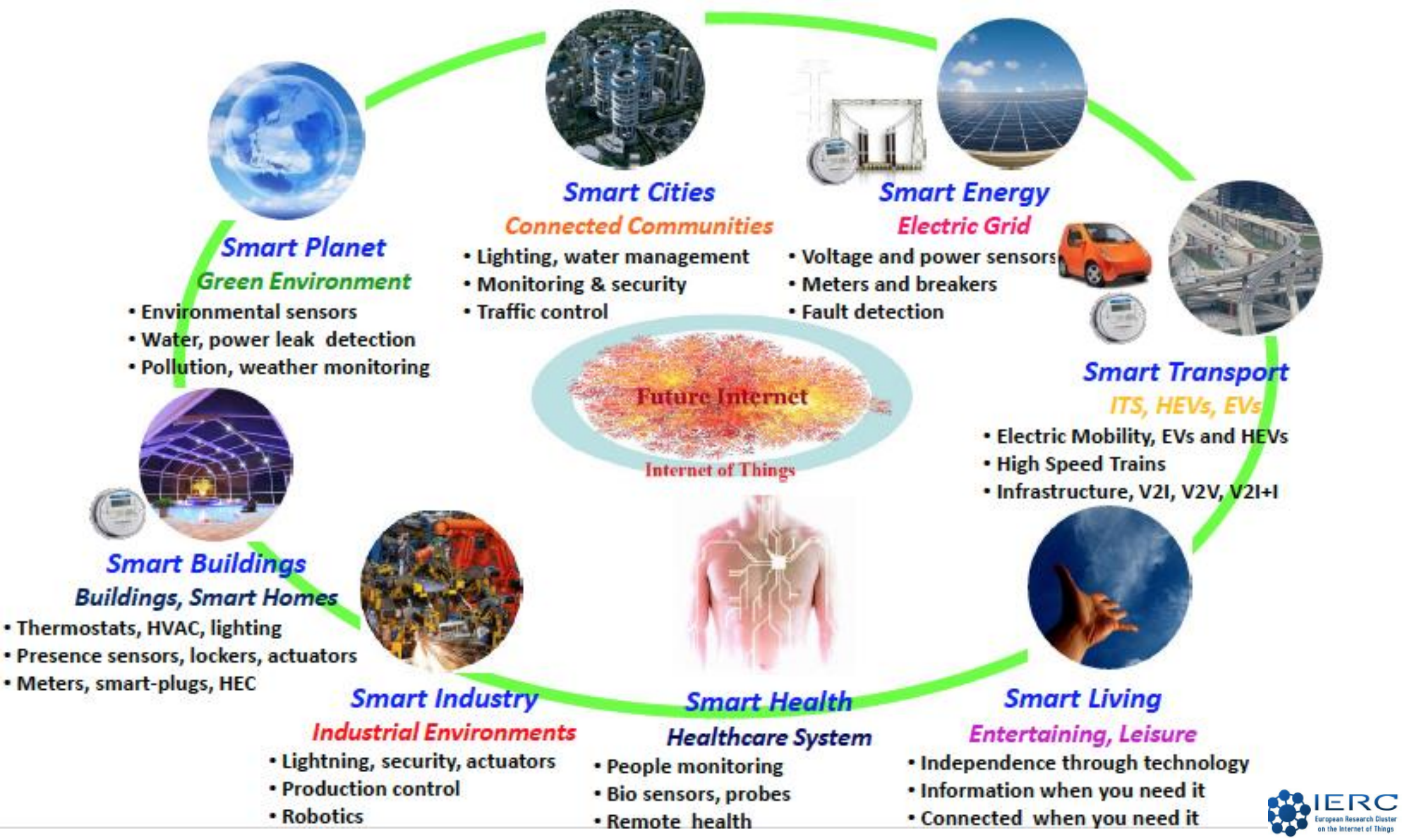
Example of a Hypothetical More-Than-Moore 3D Optical/Electronic Nanosystem



Micro- /Nano-electronics

- ≈ $300B Global Microelectronics Industry
- Microelectronics enables ‘everything’ - automotive, medical, communications, green
- The key innovation is in the Integrated Circuits
- There is a continual cycle of innovation through new products based on improvements in underlying semiconductor technology
- The next big revolution, the **Internet of Things**, will create an explosive demand for microelectronic components (e.g. predictions of 50B+ devices connected to the Internet by 2020)

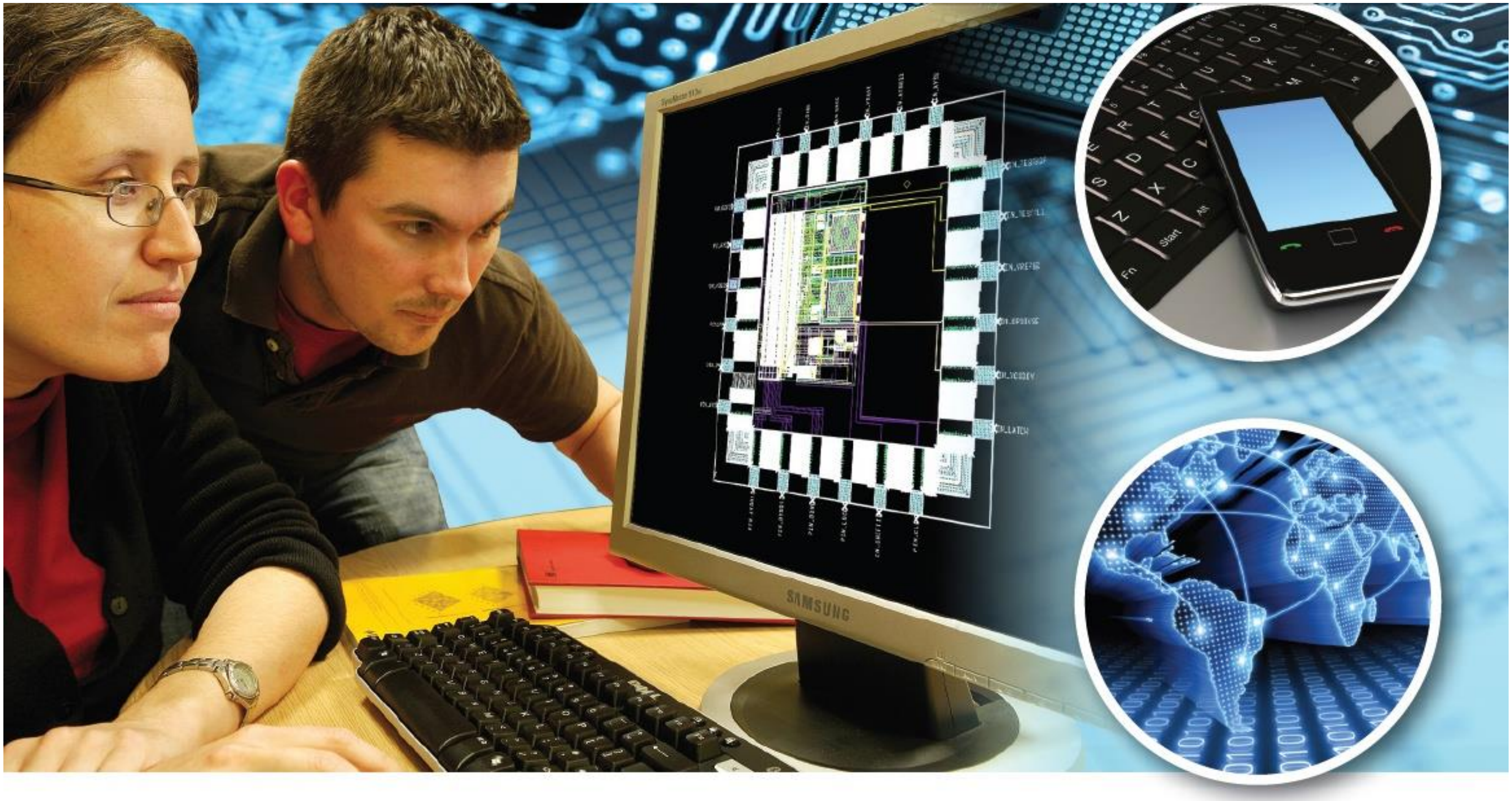
Applications of the IoT



Global challenges to be addressed by IoT: Energy Efficiency, Smart Cities, e-Health, Public Safety, Food Supply, Smart Infrastructure, Sustainable Economy, etc.

Micro-/Nano- electronics in Ireland

(with acknowledgement to John Blake of MIDAS- Microelectronic Industry Design Association of Ireland)



MIDAS Members in Ireland

Micro-/Nano- electronics in Ireland

- > 35 years of heritage, with Ireland now successfully competing on a global scale
- ≈ 60 companies with emphasis on Analog and Mixed-Signal design
- Estimate of revenue / exports = €9B pa
- Total Irish jobs in micro-electronics = 8,000
- Total business R&D = €300M pa (12% of total BERD in Ireland)
- Profile is a good mix of global leaders (through FDI – Foreign Direct Investment by MNCs – Multi-National Companies) and local start-ups

Example of a Major MNC: Intel in Ireland

- Intel came to Ireland in 1989 and has since invested billions of € in successive waves at its giant Leixlip site;
  - About 4,000 people are employed there at present;
  - The most advanced process currently in manufacture is 32nm but there is no 22nm scheduled.
  - A €500M investment was announced in early 2012, that will be the precursor to 14nm at Leixlip in the next few years

Aerial View of the Intel Fabs at Leixlip

New Science Foundation Ireland Research Professor at UCD

- Prof. Robert (Bogdan)Staszewski has been successful in his application for a highly prestigious SFI Research Professorship, valued at 5M€ which will support his research for 5 years from September 2014.
- He has simultaneously taken up his appointment as Professor of Electronic Circuits in the UCD School of Electrical, Electronic & Communications Engineering.
- His previous appointment was as professor at the Technical University of Delft, The Netherlands.
- Prof. Staszewski's research project addresses fundamental circuit challenges in the realisation of the Internet-of-Things (IoT).

Student Self-Learning: Semiconductor Processing Videos

"Foundry" IC Manufacturer (TSMC):

http://www.youtube.com/watch?v=4Q_n4vdyZzc&feature=related

"IDM" IC Manufacturer (Intel):

http://www.pcworld.com/article/227142/intel_to_bring_3d_transistors_to_nextgeneration_chips.html

Required Student Self-Learning

- A detailed handout on semiconductor fabrication processes is available for students of SSE(1) as a pdf file on Blackboard ("Processing_14_revx")
- Please download this file and study it
- The material in this handout is part of the SSE(1) course: it is fully examinable and should be considered as an assignment for self-directed learning. Note that it is NOT part of the Mid-Term Assessment in 2014/15
- Please fill out this material by personal reading of textbooks, web resources etc