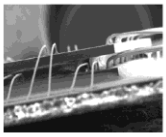
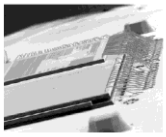
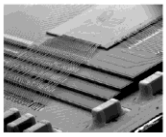
Micro and Nano- Electronics Reliability
Classical approach and new trends

Part 1: Introduction

DEFINITIONS

Quality - Reliability and Qualification

- **Quality** : degree of conformance of a product to the applicable specifications, guidelines and workmanship criteria.
- **Reliability** : extend to which a product performs its intended function under stated conditions during a specified period of time
- **Qualification** : includes all activities which ensures that the nominal design and the manufacturing will meet or exceed the reliability targets.

Failure – Failure rate

- **Failure** is the inability of the product to perform its defined mission. Failures of electronic devices, in general, can be catastrophic or non-catastrophic.
  - Catastrophic failures render the device totally nonfunctional,
  - Non-catastrophic failures result in an electrically operating device that shows parametric degradation and limited performance.
- The **failure rate** is the frequency with which an engineered system or component fails, expressed in failures per unit of time. The failure rate of a system usually depends on time, with the rate varying over the life cycle of the system (repairable systems)
- The **failure rate** is the total number of failures within an item population, divided by the total time expended by that population, during a particular measurement interval under stated conditions (batch of components)

Definitions: failure mode and mechanism

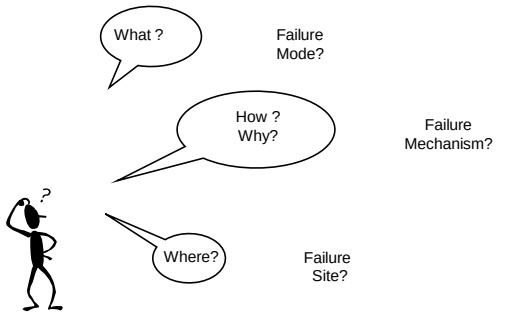
- Failure mechanism
  - The physical, chemical, electrical, thermal or other process that results in failure
- Failure modes, or observable failure events
  - Short-circuits (diodes, transistors, capacitors ...)
  - Open circuits (capacitors, resistors ...)
  - Parametric degradation
  - Limited performance

Failure mechanisms: some examples

- FEoL Failure Mechanisms
  - Time-Dependent Dielectric Breakdown (TDDB) – gate oxide
  - Hot Carrier Injection (HCI)
  - Negative Bias Temperature Instability (NBTI)
  - Surface inversion (mobile ions)
  - Floating-Gate Nonvolatile Memory Data Retention
  - Localized Charge Trapping Nonvolatile Memory Data Retention
  - Phase Change (PCM) Nonvolatile Memory Data Retention

Failure mechanisms: some examples

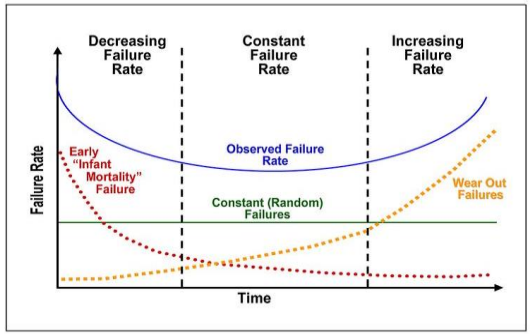
- BEoL Failure Mechanisms
  - Time-Dependent Dielectric Breakdown (TDDB)
  - Electromigration
  - Corrosion
  - Stress Migration (Al SM)
- Packaging/Interfacial Failure Mechanisms
  - Fatigue failure due to temperature cycling and thermal shock
  - Interfacial failure due to temperature cycling and thermal shock
  - Intermetallic and oxidation failure
  - Tin Whiskers
  - Ionic Mobility Kinetics (PCB) – Component Cleanliness



Classification of failures

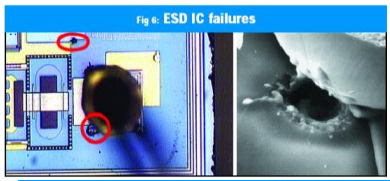
- Intrinsic Failures: due to the system it-self
  - Material
  - Design
  - Fabrication process
  - Assembly / packaging
- Extrinsic Failures: due external loads
  - Electrical Overstress (EOS) / Electrostatic discharges (ESD)
  - Handling / manipulation
  - Specification exceeded (thermal, electrical, chemical, mechanical)
  - Incorrect use

Failure rate as a function of time: “bathtub curve”



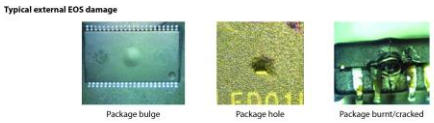
The failure rate of a system usually depends on time, with the rate varying over the life cycle of the system.

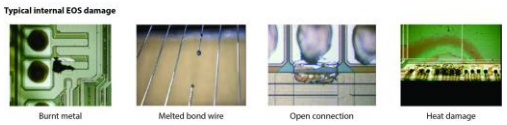
Overstress failure: examples



« IC technology and failure mechanisms » E. Moulin Industry perspective June 2004

Electrical overstress (EOS) examples



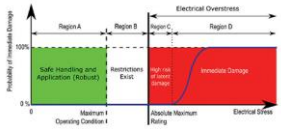


from http://www.cypress.com/file/97816/download

Electrical overstress (EOS) and ESD

EOS	***Amount*** of stress (spec was exceeded)	***quantity*** of stress
ESD	***Kind*** of stress (discharging of C)	***quality*** of stress

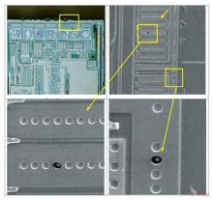
EOS and ESD are ***not alternatives*** to each other; ESD can be ***a cause*** of EOS damage

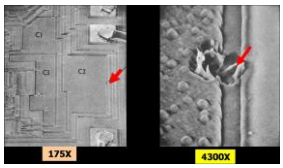


How absolute maximum ratings should be interpreted.
Blue line is the number of components suffering immediate, catastrophic EOS damage.

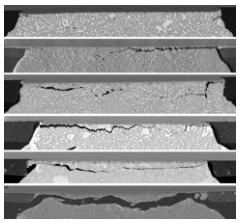
@http://incompliancemag.com/article/rethinking-electrical-overstress/

ESD induced failures

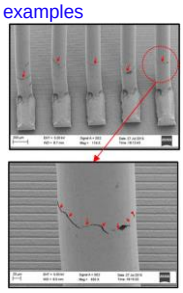




Wear-out failures: examples



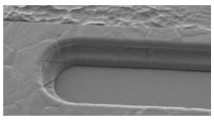
Improved Physical Understanding of Intermittent Failure in Continuous Monitoring Method
W. Maia, M. Brizoux, H. Frémont, Y. Danto
Microelectronics and Reliability, 2006,



Power cycling test and failure analysis of molded Intelligent Power IGBT Module under different temperature swing durations
U.M. Choi , F. Blaabjerga, S. Jørgensen , F. Iannuzzo , H.Wang , C. Uhrenfeldt , S. Munk-Nielsena, Microelectronics Reliability 2016

Failure Mechanisms

- Failure mechanisms of electronic semiconductor devices can be divided into the following general categories:
  - (1) Material-interaction-induced mechanisms.
  - (2) Stress-induced mechanisms.
  - (3) Mechanically induced failure mechanisms.
  - (4) Environmentally induced failure mechanisms.



Typical passivation cracks on large Al areas of a typical power IC metallization layer coated with SiN after 1000 T-cycles between −65°C and +175°C.
Ackaert, J., et Al. (ICICDT 2015).

Failure Mechanisms

- Material-induced mechanisms can in turn be subdivided into two general categories
  - Semiconductor die material and metal interactions
  - Die packaging and interconnect.
- Stress-induced failure mechanisms can be directly attributed to either poor device design or poor and careless device application.
- Environmentally induced failure mechanisms can cover a wide spectrum of possible environmental conditions
  - Humidity
  - Temperature
  - Chemical agents
  - Mechanical fatigue

Failure Modes and Mechanisms: Example

Table 4-1. Common MMIC failure modes.

Failure Mode	Method of Detection	Related Failure Mechanisms	Possible Solutions
Degradation in I_{DSS}	Life test, operation	Gate sinking, surface effects, hydrogen effects	Derating criteria, temperature control, environmental control
Degradation in gate leakage current	Life test, high-temperature storage test, high-temperature reverse bias	Interdiffusion	Temperature control, gate current control, proper passivation
Degradation in V_P	Life test, operation	Gate sinking, hydrogen effects	Temperature control, use of stable barrier materials, environmental control
Increase in R_{DS}	Life test, operation	Gate sinking, ohmic contact degradation	Temperature control, use of stable barrier materials
Decrease in P_{OUT}	Life test, operation	Surface effects, hydrogen effects, gate sinking	Temperature control, use of stable barrier materials, environmental control

Failure sites, mechanisms and condition monitoring (examples on IGBT)

Failure sites		Failure modes	Failure mechanisms	CM Parameters
Die level	Die	Short circuit, burnout, loss of gate control	Latch-up and secondary break-down	$V_{CE,on}$ t_{off} $V_{GE,th}$
		Short circuit, loss of gate control	Time dependent dielectric break-down	V_{GE} $V_{GE,th}$
Package level	Bonding wire: bond	Bond wire liftoff	Fatigue and/or recon-struction	t_{on} t_{off} $V_{CE,on}$ V_{GE}

Failure sites, mechanisms and condition monitoring (examples on IGBT) *(2)*

Failure sites		Failure modes	Failure mechanisms	CM Parameters
Package level	Bonding wire: heel	Bond wire heel cracking	Fatigue	
	Bonding wire: body	Open wire	Stress corrosion	
		Wire burnout	Joule heating	
	Solder joint	Solder joint cracks	Fatigue or grain growth	R_{th}, $V_{CE,on}$ t_{off} Low-order harmonics

FEOL related failure modes and mechanisms examples in CMOS devices

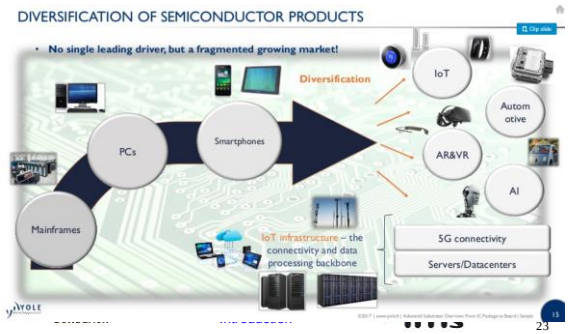
- Failure Mechanisms
  - Time Dependent Dielectric Breakdown (TDDB)
  - Bias Temperature Instability (BTI)
  - Hot Carrier Injection (HCI)
  - Mobile Ion Contamination
  - Plasma-processing Induced Damage (PPID)
  - Random Telegraph Noise (RTN)
  - Electrostatic Discharge (ESD)
  - Latch-up
  - Soft Error Rate (SER), …

Failure Modes

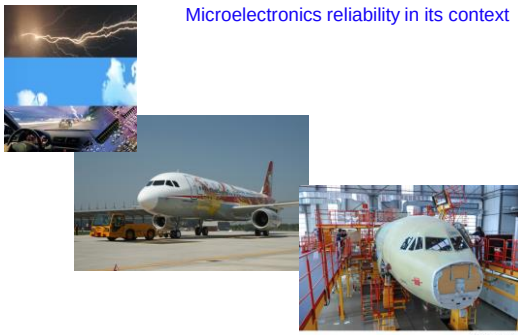
- Gate current increase
- Threshold voltage shift
- Drain current degradation
- …

Why learn about Reliability?

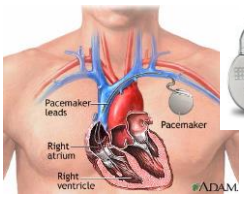
Microelectronics reliability in its context



Microelectronics reliability in its context



Microelectronics reliability in its context




Real Case

- Malfunction identified in pacemaker microprocessor which may lead to single chamber atrial pacing
- Potential of being catastrophic for pacemaker dependent patients with total AV nodal block.
- Number of units distributed: 144000 units
- Failure rate: 0.00014
- 1371 elective explants resulting from the advisory notice.
- 8 failures identified in the 1371 devices (0.006%). One having the potential for serious patient injury.
- No serious injury reported.

ST. JUDE MEDICAL

Microelectronics reliability in its context




Microelectronics reliability in its context



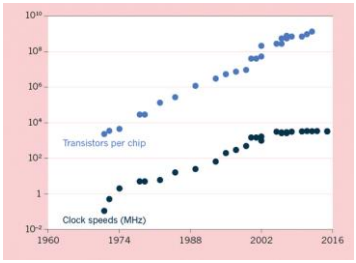
The challenges

The challenges

- Moore's Laws
  - Since the invention of the integrated circuit in 1958, the number of transistors that can be placed inexpensively on an integrated circuit has increased exponentially, doubling approximately every two years. The trend was first observed by Intel co-founder Gordon E. Moore in a 1965 paper. It has continued for almost half a century and in 2005 was not expected to stop for another decade at least.
- More than Moore's

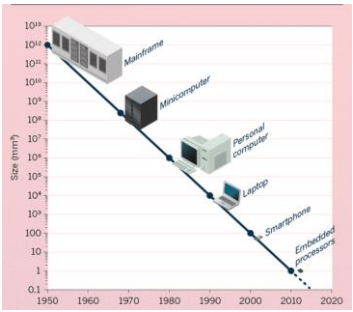
- Beyong CMOS: Emergent technologies

Moore's Laws



https://www.nature.com/news/the-chips-are-down-for-moore-s-law-1.19338
Mitchell Waldrop - Nature 2016 (source Intel)

Moore's Laws

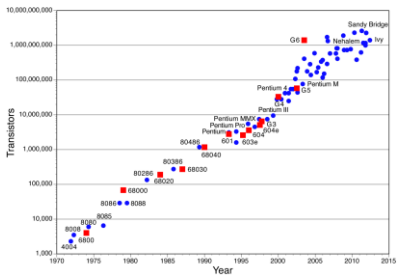


https://www.nature.com/news/the-chips-are-down-for-moore-s-law-1.19338
Mitchell Waldrop - Nature 2016
source SIA/SRC

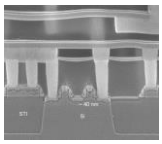
Moore's Laws

- Almost every measure of the capabilities of digital electronic devices is strongly linked to Moore's law: processing speed, memory capacity, sensors and even the number and size of pixels in digital cameras.
- All of these are improving at (roughly) exponential rates as well. This has dramatically increased the usefulness of digital electronics in nearly every segment of the world economy.
- Moore's law describes this driving force of technological and social change in the late 20th and early 21st centuries.

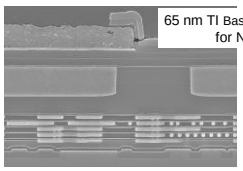
Moore's law for memory chips and microprocessors



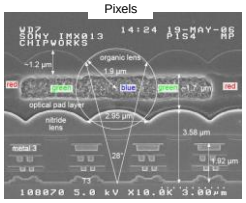
The uppermost purple curve is the Moore projection based on data up to 1975; note the kink correction around 1980, which shows that the so-called law is only an approximation. [Source: Intel Corporation]
http://www.wsj.com/articles/moores-law-runs-out-of-gas-1429282819
Moore's Law: More or Less? May, 2007 by Neil J. Gunther

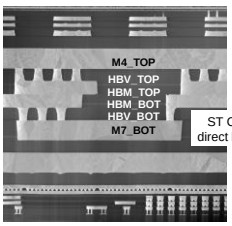


TSMC 65 nm Poly and Substrate –Chipworks



65 nm TI Baseband Chip for Nokia



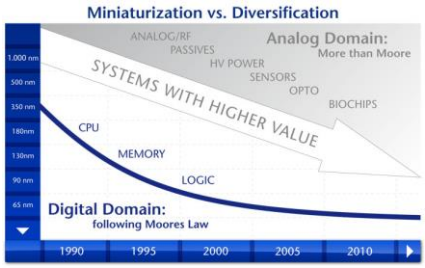


ST Cu-Cu direct bonding

"More than Moore"

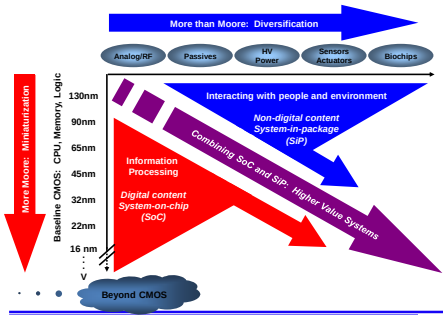
- Diversification of technologies within a chip or a package
  - Radio frequency (RF) devices
  - Power management subsystems
  - Passive components
  - Biochips
  - Sensors
  - Actuators
  - Microelectromechanical systems (MEMS)
- Integrating analog functions into CMOS-based specialty technologies enables cost-optimized and value-added system solutions.

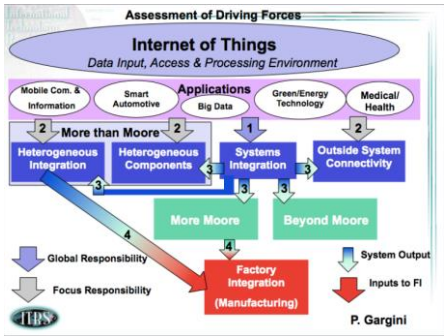
More than Moore

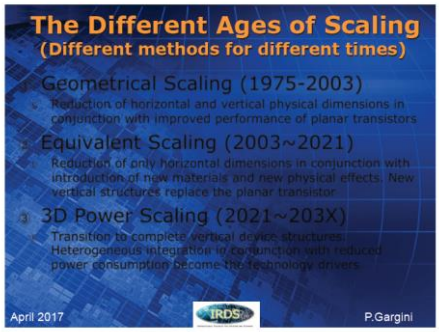


Moore's Law & More

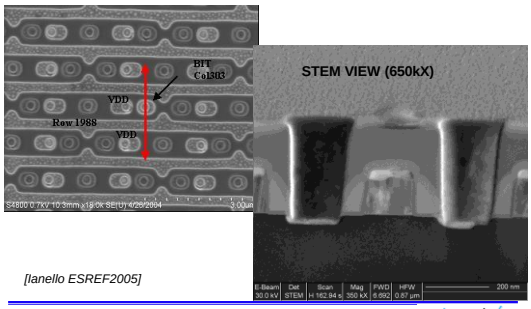
ITRS public conference
San Francisco July 13, 2010





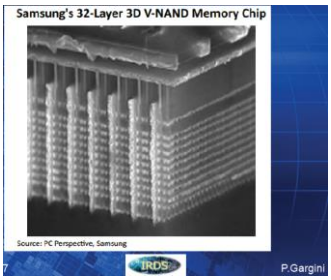


Pitch reduction

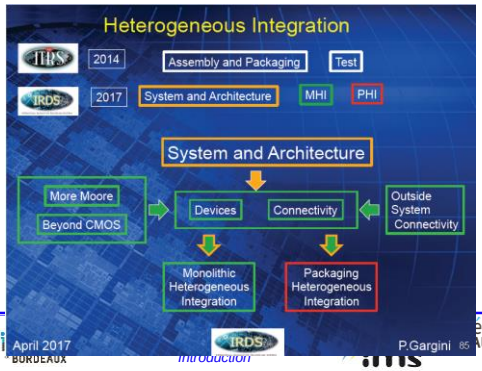


[Ianello ESREF2005]

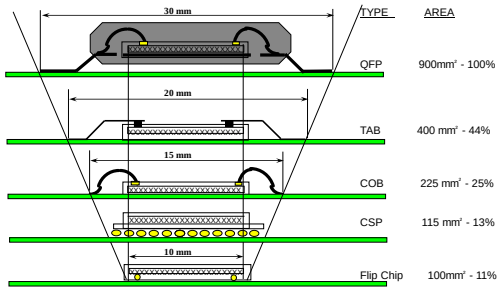
3 D integration



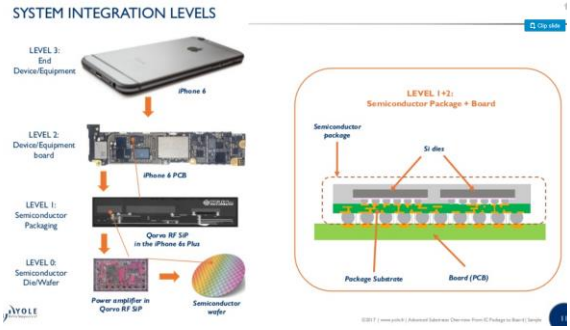
Function complexification



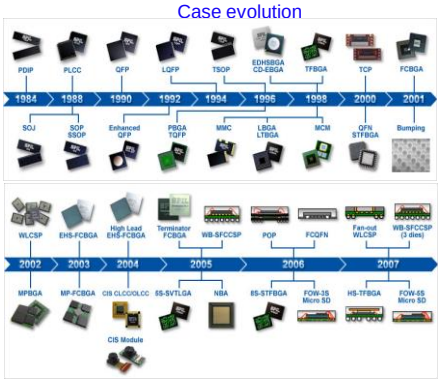
Report on PCB



SYSTEM INTEGRATION LEVELS



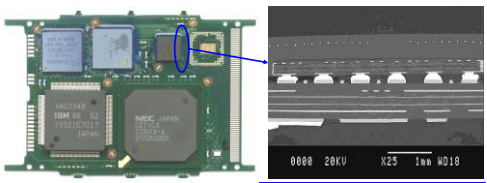
Case evolution

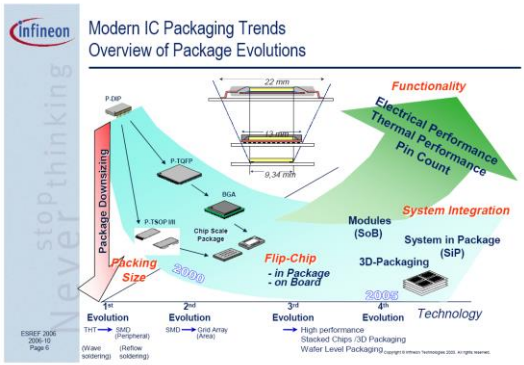


Siliconware Precision Industries Co http://www.spil.com.tw

Example: complex composite assembly

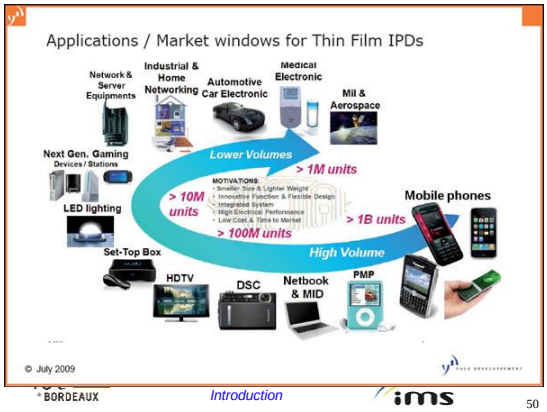
- Technological parameters
  - Geometries, dimensions
  - Materials
  - Soldering/ adhesive bonding
  - Case types
  - Number of interconnection layers

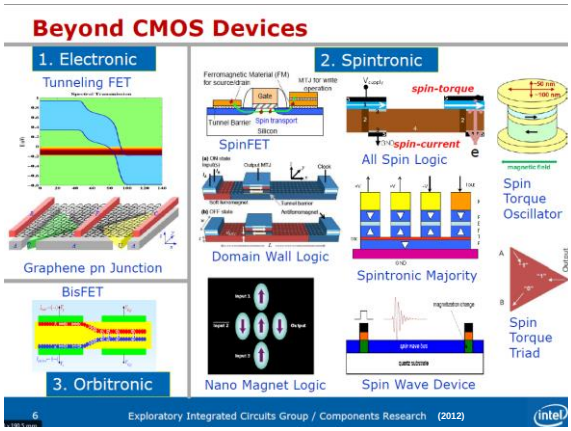


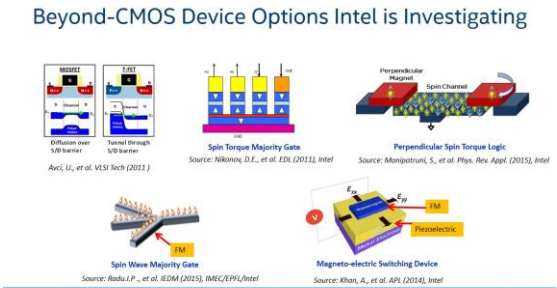


Challenges

- Multi-scale in both geometric and time domains
- Multi-technology, multi-loading and multi-discipline
- Multi-material and multi-interface
- Multi-failure mechanism, multi-failure mode and multifailure location
- Strongly non-linearity
- Stochastic in nature
- Strongly time and temperature dependent

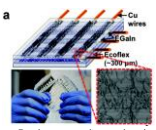






Emerging materials and technologies

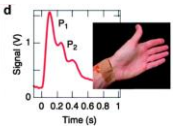
Flexible inorganic LED Displays (2009)



Some biological and biomedical applications of organic electronics.

O'Connor, et al. "Toward organic electronics with properties inspired by biological tissue." *Journal of Materials Chemistry B* (2015).

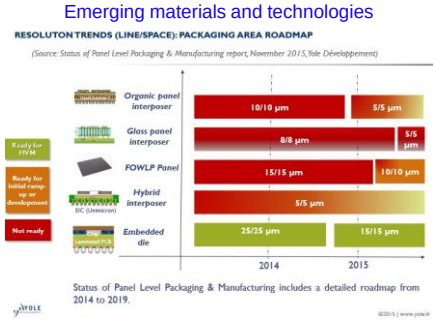
Random composites, such as bundles of buckled carbon nanotubes, can be used to form stretchable, transparent, skin-like sensors of pressure and strain.



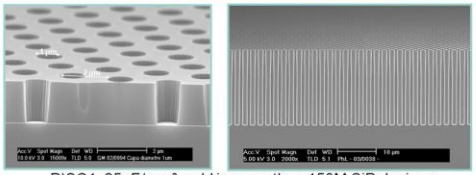
c) "Imperceptible" organic electronic devices built on ultrathin (<2 μm) polyester foils can easily conform to biological structures exhibiting complex topography.

d) An organic thin-film transistor bearing a compressible dielectric layer can transduce the mechanical deformation of the radial artery into the pulse waveform

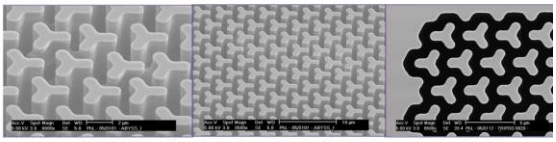
Emerging materials and technologies



Two types of pit capacitors: 25 and 80 nF/mm2



PISC1: 25nF/mm², sold in more than 150M SiP devices



PISC2: 80nF/mm², Just qualified – 250nF/mm² demonstrated

Reliability: challenges

- Reliability is an important factor in any semiconductor or packaging process technology development.
- As a consequence of the strong reduction in geometries, the internal electrical fields and current densities are continuously increasing, leading to a number of reliability problems, such as
  - time-dependent dielectric breakdown,
  - hot carrier degradation,
  - electro-migration
  - stress induced voiding, etc.

Reliability

- The devices and circuits are becoming more vulnerable to effects such as electrostatic discharge (ESD), which strongly limits not only the reliability but also the yield of the circuits.
- New materials, such as high-k gate dielectrics and Cu and low-k materials, and new device architectures such as multiple gate FETs as well as new technologies like micro-electromechanical systems (MEMS) and packaging technologies are introduced.
- For these new materials, devices and technologies the failure mechanisms are still not well understood and their speed of introduction exceeds the capability to explore their reliability.

Challenges linked to new technologies

- Multi-scale in both geometric and time domains
- Multi-technology, multi-loading and multi-discipline
- Multi-material and multi-interface
- Multi-failure mechanism, multi-failure mode and multi-failure location
- Strongly non-linearity
- Stochastic in nature
- Strongly time and temperature dependent