Delivering complexity at the frontier of electronics

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Complexity Sells

- Enables the impossible to become possible
- Complexity that enables simplicity of use
- Complexity can take many forms (density, structure, data, function, ...) but ultimately people pay for use
- Delivering complexity makes our business go!
“Any sufficiently advanced technology is indistinguishable from magic”
- Arthur C. Clarke 1973

Intel 2013

Every 2 years
Intel delivers a new manufacturing process

2x Better
than the previous generation

Intel in the Future

1 x 10^9
1 billion transistors fit into an area of One square centimeter

~1 x 10^18
Intel ships about one quintillion transistors per year
We Need Both New Materials & New Structures

Increasing Coupling
"idle power"
Planar With High K

Increasing Mobility
"performance"
(can trade for power)
Strain

Fins & Multigate

PMOS Ieff @ 0.7V (Normalized)
Proc. of SPIE Vol. 8880  888002-5
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High Performance Computing Segment Needs
Decades of Performance Increases
FLOPS
Zeta
Exa
Pera
Tera
Giga

Sauce: Itatmessor MeetmGoS23

Need Multiple Applied Sciences to reap benefits

Crafting Films with Atomic Layer Deposition

X-ray Space Telescope
Multi-layer Coatings
EUV Lithography

Precision Mirrors

Immersion Lithography

Materials Synthesis
Computational Materials

X-ray Space Telescope
Precision Mirrors
Immersion Lithography

Need Multiple Applied Sciences to reap benefits

Computational Materials

Materials Synthesis

Proc. of SPIE Vol. 8880 888002-6
The Evolution of Personal Computing

Productivity
80s and 90s

Portability
00s

Ubiquity
10s
What Happens in an Internet Minute?

639,800 GB of global IP data transferred

- 6 Botnet infections
- 135 New mobile users
- 1,300 New victims of identity theft
- 61,141 New Wikipedia articles published
- 204 million New victims of identity theft
- 583,000 New victims of identity theft

639,800 GB of global IP data transferred

- 20 App downloads
- 204 million Emails sent
- 47,000 Photo views
- 20 million Photo uploads
- 2 million Photo uploads
- 100,000 New Twitter accounts

And Future Growth is Staggering

Today, the number of networked devices = the global population

By 2015, the number of networked devices = 2x the global population

In 2015, it would take you 5 years to view all video crossing IP networks each second

Proc. of SPIE Vol. 8880 888002-9
Key Points

• Complexity just from density is insufficient and it has been that way for a decade or more ... increasing value from structure (materials), functions, and data

• Complexity that enables simplicity of use is driving the end market more today than in the past

• Delivering complexity at the right price point makes our business go!
The (likely) near future
Optimizing Choices for Transistors on Multiple Fronts

- Increasing COUPLING (better OFF)
  - Planar with High K
  - UTB SOI (or QW)
  - Fins
  - Wires/Dots

- Increasing MOBILITY (better ON)
  - Strain
  - Ge
  - III-V
  - CNT
  - Graphene
Optimizing Choices for Printed Information

Line Double (& Quadruple)

Dense but low information

High customization

Some useful design

Direct Write

EUV

193i

Single exposure limit

Pattern Split

Cost proportional to information

Cost/Vol Tradeoff
The Gate All Around (GAA) Architecture is the Limit to Structural Electrostatic Control

Source: K. Kuhn et al. TED 59:7 2012
Increasing Capability (Information) of a Single Mask

Conventional Mask Structure

Alternate Phase Shift

More printed information
For given tool capability

Higher information density

Source: P. Yan, SPEI 2011
Are there fundamental physical limits?

- 5nm device structures have been demonstrated in research labs
- New device architectures are under investigation

Our ability to control is more a limitation than the physics
Control implies we can measure and co-optimize
Managing Material Properties at Nanometer Scale

Grain scattering dominates
Need sub-nm material engineering

Cu wires at 17nm drawn dimension
(colors indicate crystal orientation)
Another Sub-nm Example

Pit defect
50 pairs Mo/Si

Bump defect
40 pairs Mo/Si

TEM of 50-pair ML
covered 11nm etched step

Source: Courtesy of SEMATECH and P. Yan, SPEI 2011
How Small Can We Fabricate and Control?

“Self-Assembling Materials for Lithographic Patterning”
Bill Hinsberg et al, IBM.SPIE 2010

7nm half-pitch
IBM, Park et al, Nanotech 19 2008

Cai et al, Nature July 2010
Control Requires Co-Optimization

Production Share
Has dramatically shifted into captive production

Source: Courtesy of VLSI Research 2013
Inflection Points

Granularity
Size limited by Electrical behavior
Voltage scaling limited by Mobility
Interconnects limit performance

“The only way of discovering the limits of the possible is to venture a little way past them into the impossible”
- Arthur C. Clarke 1962
Alternative paths

Source: Google Earth

Magic Roundabout, Swindon, UK
Future systems will integrate a much wider variety of materials and device structures.

Source: IEDM 2011: The Evolution of Scaling from the Homogeneous Era to the Heterogeneous Era, M. Bohr
Layer Stack Density Benefit: 30-50%

Widespread use requires new design methods ... and some new metrology
Beyond CMOS Devices - Noncharge

Spin Torque Majority Gate (STMG)
All Spin Logic (ASLD)
Spin Torque Domain Wall (STT/DW)

Spin Torque Oscillator (STO)
Spin Wave Device (SWD)
Nanomagnetic Logic (NML)

Source: D. Nikonov and I. Young, 2012 IEDM
Exploring Other Ways to Compute

Memory & Storage

Fetch

Store

Compute & Decide

Slower & larger

Faster & smaller

“Von Neumann”

Bottleneck = memory/storage
Transport limited devices make it worse

Unknown

Associate & Decide

Training set

Act

Bottleneck = training
Potentially favorable for novel devices
The Future of Mask Fabrication?

Massively parallel beam writing
Parallel beam writing
VSB (vector writing)
MEBES (single beam raster)
Key Messages

• Complexity sells ... and thus complexity is your friend

• Novel materials in complex 3D structures are here now and will be increasingly prevalent in the future

• Today we have even more choices than we have had in the past – this is both good and bad

• The future remains bright and masks remain an integral part of our future success
Thank You
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