Delivering complexity at the frontier of electronics

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Event: SPIE Photomask Technology, 2013, Monterey, California, United States
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

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

Intel 2013

Every 2 years
Intel delivers a new manufacturing process

2 x Better
than the previous generation

Intel in the Future
We Need Both New Materials & New Structures

Increasing Coupling

"idle power"

Planar With High K

Fins & Multigate

Increasing Mobility

"performance"
(can trade for power)

Strain

PMOS Ieff @ 0.7V (Normalized)

Generation (nm)

Tri gate
Strain
Classic

Proc. of SPIE Vol. 8880  888002-5
High Performance Computing Segment Needs
Decades of Performance Increases
FLOPS
Zeta
Exa
Pera
Tera
Giga

Need Multiple Applied Sciences to reap benefits

X-ray Space Telescope

Multi-layer Coatings

Precision Mirrors

EUV Lithography

Immersion Lithography

Crafting Films with Atomic Layer Deposition

Materials Synthesis

Computational Materials

X-ray
Space
Telescope

Precision
Mirrors

Immersion
Lithography

Multi-layer Coatings

EUV Lithography

Computational
Materials

Need Multiple Applied Sciences to reap benefits
Level of detail

- No OPC
- Model/Rule based OPC
- Aggressive OPC + assist features
- Inverse lithography

1 billion transistors
60 billion design features
1 trillion mask features
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
- 135 Botnet infections
- 1,300 New mobile users
- 100+ New LinkedIn accounts
- 277,000 Logins
- 6 million Facebook views
- 2+ million Search queries
- 30 Hours of video uploaded
- 1.3 million Video views
- 3,000 New Twitter accounts
- 100,000 New tweets
- 47,000 App downloads
- 583,000 In sales
- 61,141 Hours of music
- 20 million Photo views
- 204 million Emails sent
- 20 New victims of identity theft
- 47,000 New Wikipedia articles published
- 20 App downloads
- 100+ New mobile users
- 277,000 Logins
- 6 million Facebook views
- 2+ million Search queries
- 30 Hours of video uploaded
- 1.3 million Video views
- 3,000 New Twitter accounts
- 100,000 New tweets
- 47,000 App downloads
- 583,000 In sales
- 61,141 Hours of music
- 20 million Photo views
- 204 million Emails sent
- 20 New victims of identity theft
- 47,000 New Wikipedia articles published

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

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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

Some useful design
Line Double (& Quadruple)
Dense but low information
High customization
Cost/Vol Tradeoff

EUV 193i
Single exposure limit
Pattern Split
Direct Write

Cost proportional to information

Proc. of SPIE Vol. 8880  888002-13
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

More printed information For given tool capability

Higher information density

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

5nm device feature

Vertical device structures and new materials

- 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
Heterogeneous System Integration

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%

Stacked Latch

Widespread use requires new design methods
... and some new metrology

Source: STM/Leti, 2009 IEDM
## Beyond CMOS Devices - Noncharge

### Devices

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin Torque Majority Gate (STMG)</td>
<td></td>
</tr>
<tr>
<td>All Spin Logic (ASLD)</td>
<td></td>
</tr>
<tr>
<td>Spin Torque Domain Wall (STT/DW)</td>
<td></td>
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<tr>
<td>Spin Torque Oscillator (STO)</td>
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<tr>
<td>Spin Wave Device (SWD)</td>
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<tr>
<td>Nanomagnetic Logic (NML)</td>
<td></td>
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</tbody>
</table>

**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

Associate & Decide

Act

Unknown

Training set

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
Risk Factors

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