Delivering complexity at the frontier of electronics

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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!
You Are Here
"Any sufficiently advanced technology is indistinguishable from magic"
- Arthur C. Clarke 1973

Intel 2013

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

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) vs. Generation (nm)
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
6 New Wikipedia articles published

61,141 Hours of music

204 million Emails sent

583,000 In sales

200 million Photo views

277,000 Logins

2+ million Search queries

1,300 New mobile users

100+ New LinkedIn accounts

47,000 App downloads

6 million Facebook views

320+ New Twitter accounts

6 million Photo uploads

100 million Photo uploads

100,000 New tweets

20 million New victims of identity theft

3,000 New Twitter accounts

320+ 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

IP

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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

Intel

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Optimizing Choices for Printed Information

Some useful design

High customization

Cost/Vol Tradeoff

Direct Write

EUV
Single exposure limit

193i

Pattern Split

1 + ? =

Cost proportional to information

Dense but low information

Line Double (& Quadruple)
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 feature

Vertical devices

III-V Vertical Tunnel FETs

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
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
Beyond CMOS Devices - Noncharge

<table>
<thead>
<tr>
<th>Spin Torque Majority Gate (STMG)</th>
<th>All Spin Logic (ASLD)</th>
<th>Spin Torque Domain Wall (STT/DW)</th>
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<td>Spin Torque Oscillator (STO)</td>
<td>Spin Wave Device (SWD)</td>
<td>Nanomagnetic Logic (NML)</td>
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Source: D. Nikonov and I. Young, 2012 IEDM
Exploring Other Ways to Compute

Memory & Storage

Fetch

Slower & larger

Compute & Decide

Faster & smaller

Store

“Von Neumann”

Bottleneck = memory/storage

Transport limited devices make it worse

Unknown

Associate & Decide

Training set

Act

Bottleneck = training

Potentially favorable for novel devices

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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
Risk Factors

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