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Delivering complexity at the frontier of electronics

Michael Mayberry

Michael C. Mayberry, "Delivering complexity at the frontier of electronics,"
Proc. SPIE 8880, Photomask Technology 2013, 888002 (22 October 2013);
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SPIE.

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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

1×10^9

1 billion transistors
fit into an area of
One square centimeter

$\sim 1 \times 10^{18}$

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

X-ray
Space
Telescope

Precision
Mirrors

Immersion
Lithography

Multi-layer
Coatings

EUV
Lithography

Crafting Films with Atomic Layer Deposition

**Need Multiple
Applied Sciences
to reap benefits**

High Performance Computing Segment Needs
Decades of Performance Increases

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?

And Future Growth is Staggering

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

Cost/Vol
Tradeoff

Direct Write

Cost proportional
to information

EUV

193i

Single exposure limit

Pattern Split

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

Source: P. Yan, SPIE 2011

Are there fundamental physical limits?

5nm device feature

Source: Endoh, TED 2003

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, SPIE 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

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

Source: STM/Leti, 2009 IEDM

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

*Bottleneck = memory/storage
Transport limited devices make it worse*

*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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