SRC: Celebrating 30 Years

Working together we are formidable!

Authors

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Outline

- The Early Years
- The Enduring Role of Citations
- Research Funding History
- Origins of the Research Agenda
- Industrial Liaison Program
- Industry Feedback on Research
- Our University Partners
- Examples of Impact on our Members
- Celebrating Research Accomplishments
- SRC Start-Ups and Intellectual Property
- Forecasting Future Member Technologies from the Current Portfolio
- Challenges and Opportunities
- Back-up Citation Data

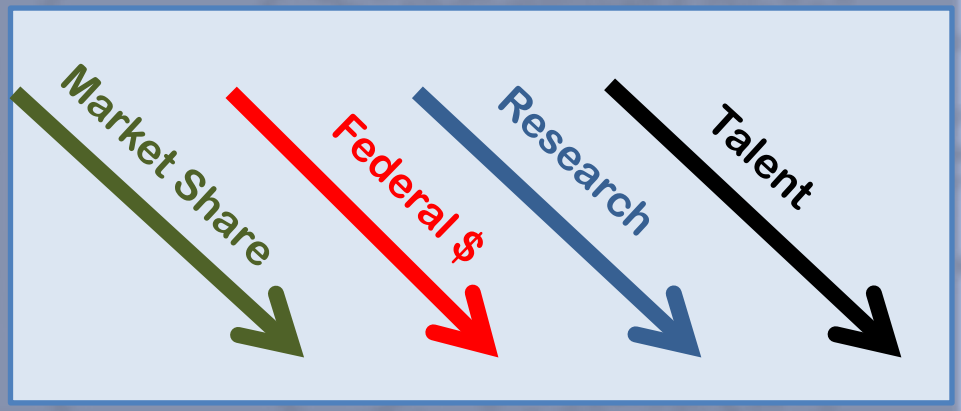
The Semiconductor Environment in 1982

U.S. semiconductor companies were rapidly losing market share and federal support for silicon research was decreasing.

Very little silicon-oriented research was being conducted in universities.

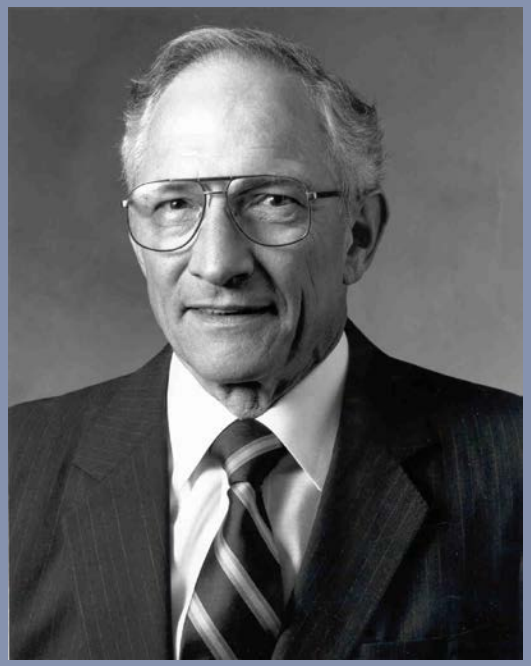
- Less than 100 students and faculty conducted silicon research.

As a result, the pipeline of talent was drying up.



What happened?

- In 1982, the Semiconductor Industry Association formed the SRC to launch and manage relevant and collaborative university research programs.



- Robert Noyce of Intel wrote a personal check to Larry Sumney, the SRC's founding President, to begin SRC operations.

SRC's Charter (1982)

Objectives:

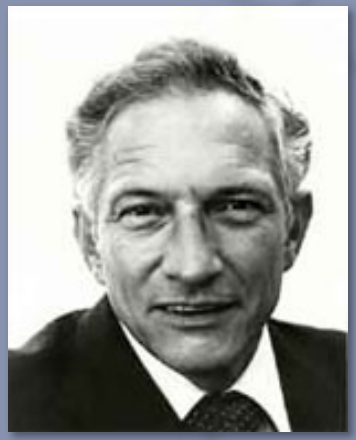
- Define relevant research directions
- Explore potentially important new technologies (and transfer results to industry)
- Generate a pool of experienced faculty & relevantly educated students

Visionary Leadership for SRC

First SRC Board Chair

Erich Bloch

SIA Board

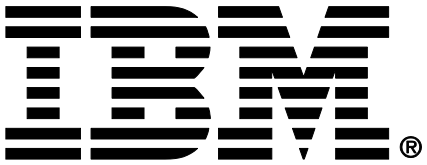


Robert Noyce

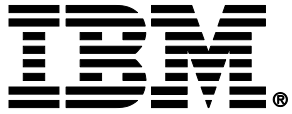
SRC IP Policy

Jack Kilby

Founding SRC Companies

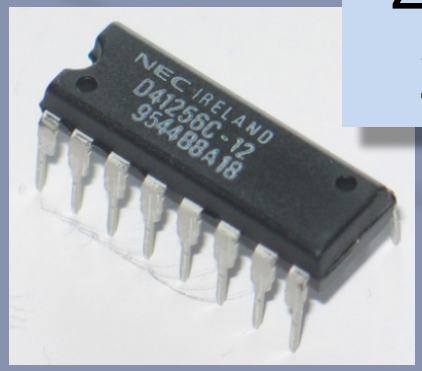


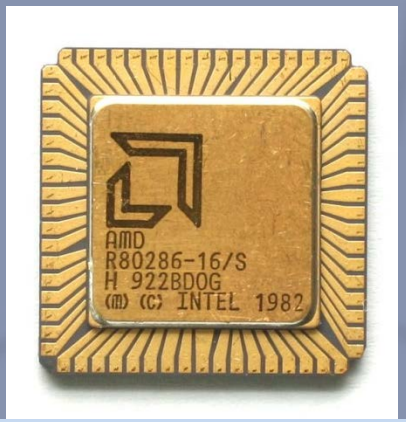
Current SRC Member Companies



Semiconductor Landscape in 1982

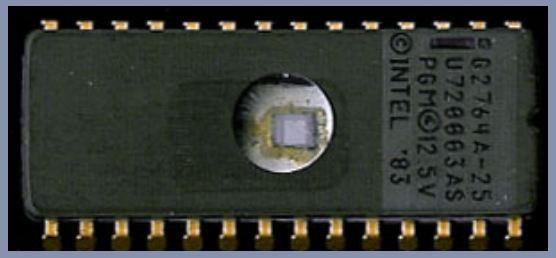
256 Kbit DRAM
2 μm features

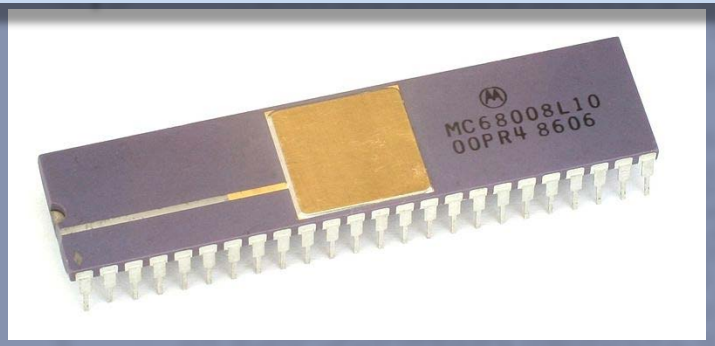




10^5 transistors/MPU
10 MHz
1.5 μm features

64 Kbit UV-EPROM
No flash memory as we know it today





What 30 Years of Progress Enabled

1976: Best available storage technology was the **IBM 3350**

80Gb cost
$9,000,000 !!!
in 1976 dollars

126 IBM 3350's = storage in **1 iPod**

2006

iPod(5G)
80GB

80Gb cost
$350
in 2006 dollars

1982: SRC 'Springs into Action'

166 proposals received → 80 proposals funded

↓

Three research centers were formed

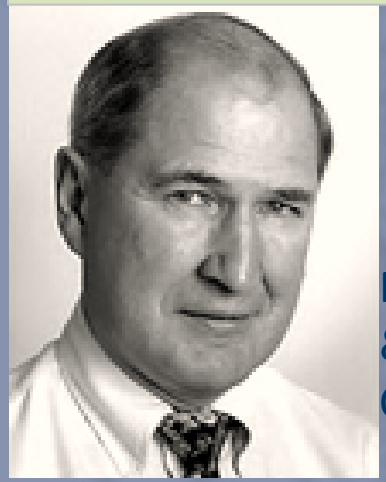
SRC-CMU Center of Excellence for CAD

Steve Director, CMU

SRC-UC/Berkeley Center of Excellence for CAD

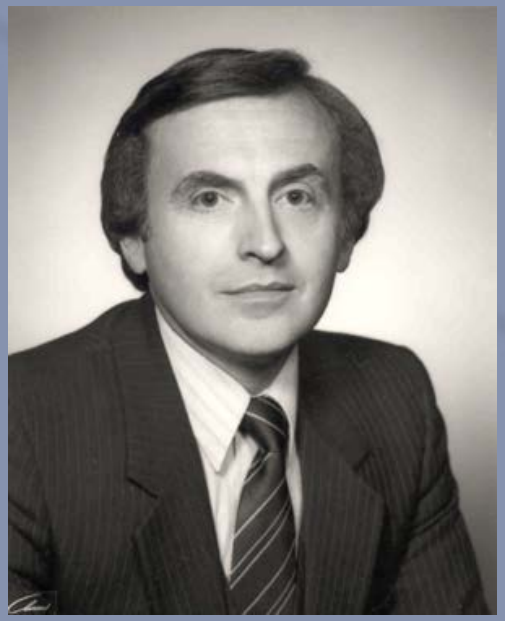
Don Pederson, UC-Berkeley

SRC-Cornell Center of Excellence for Microscience & Technology



Noel MacDonald & Jeffrey Frey, Cornell

SRC Senior Staff (Circa 1982)



Larry Sumney

Robert Burger & Richard Alberts

Example 10-year SRC Research Goals (1984)

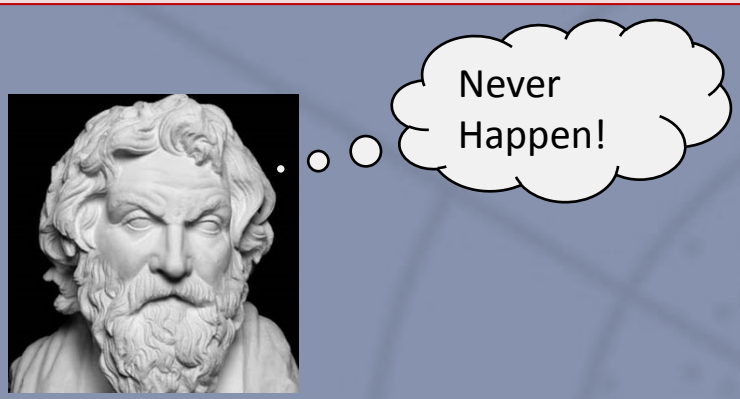
- ✓ **256Mb** DRAM with **0.25 micron** minimum feature size
- ✓ **50 ps** logic gate delay and switching energy of **5 fJ**
- ✓ **Six person-month** design time for error-free layout of chips with **10^8** transistors
- ✓ Tests that enable less than **1 in 10^6** defective devices
- ✓ **5X** increase in manufacturing productivity

SRC Goals Were Sometimes Met With Disbelief

- "0.25 micron minimum features – doesn't that violate the laws of physics?"

  *"It is doubtful that one can scale the device dimensions to **below 0.1 μm** and gain any advantage in circuit performance because of several **basic limitations.**"*

  Proc. IEEE (1983): *"A systems approach to 1 μm NMOS"*



- Working together, we achieved the 1984 SRC goals!

Return to Outline

What is a citation?

A citation is a reference to an earlier paper by subsequent authors.

- Only about 2% of all papers achieve 100 citations.
- 100 citations qualifies an SRC paper for "Influential Status" – comparable to Nobel Laureates in the semiconductor field.
- Papers that continue to receive citations long after they were published are very rare.

Times Higher Education World University Rankings since 2010 uses citations as a ranking indicator – **32.5% weightings.**

SRC uses industrial citations as a 'quality indicator' for SRC-funded research.

SRC Influential Publications

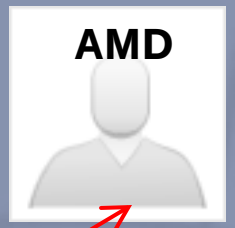
- Currently, 210 SRC- supported papers have been identified to have received over 100 citations.

- Almost 2/3 of SRC's Influential Publications have received at least 15% industry citations.

Early Success (1984)

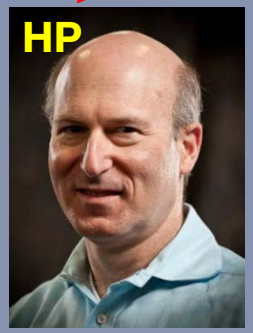
0.25 micrometer CMOS Thrust
(U Illinois)

TSMC (VP of R&D)



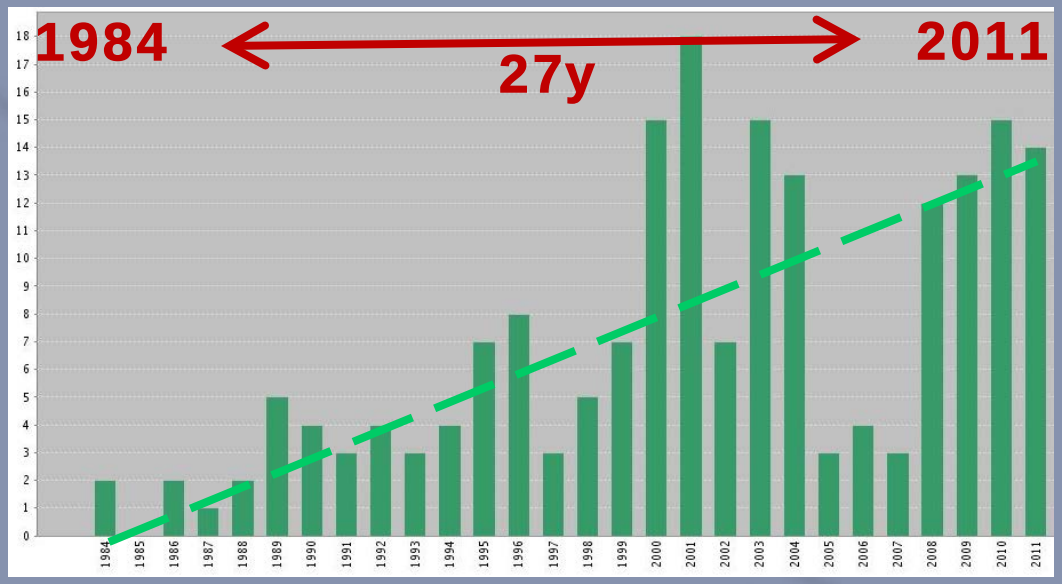
Project started	Paper Title	Authors	Total Citations	Industry Percentage	Category
1983	"Study of the atomic models of 3 donorlike defects in silicon metal-oxide-semiconductor structures from their gate material and process dependencies", JAP 55 **(1984)** 1525	**CT Sah**, Jack Y.-C. Sun, Joseph J. Tzou	**101**	**36%**	**Technology**
1982	"Full-speed testing of A/D Converters", IEEE J. of Solid-state Circ. 19, **(1984)** 820	Joey Doernberg, Hae-Seung Lee, **David Hodges**,	**193**	**32%**	**Design**

CAD Thrust
(UC Berkeley)



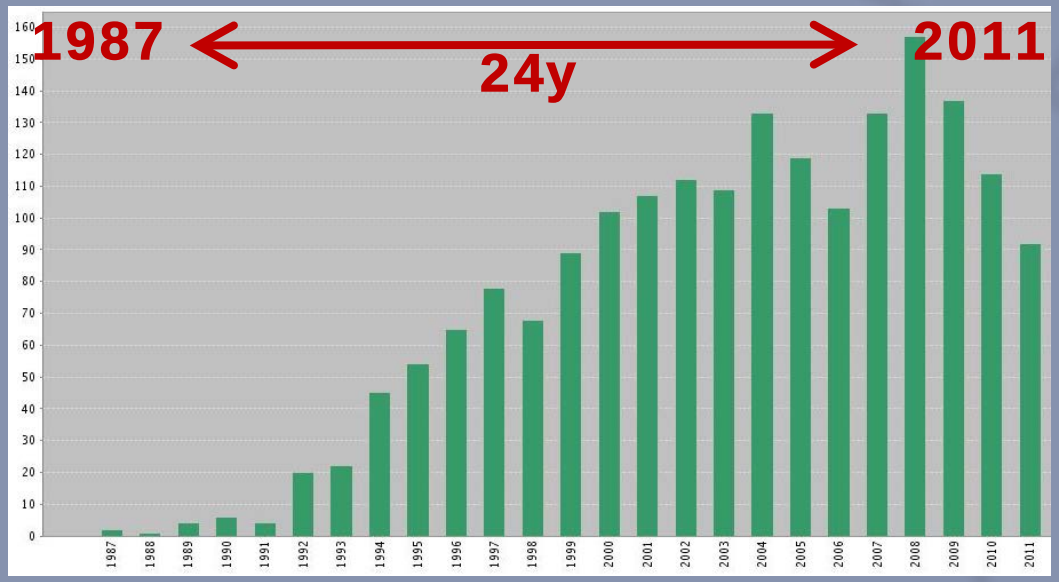
MIT (professor) Cambridge Analog Technol. (co-founder)

Foundational work is long lasting!



Decades of growing interest!

"Full-speed testing of A/D Converters", IEEE J. of Solid-state Circ. 19, (1984)



“Graph-based algorithms for Boolean function manipulation”, IEEE Trans on Comp. 35 (1986)

Early Research on Algorithms

Project started	Paper Title	Authors	Total Citations	Industry Percentage	Category
1982	"Randomized Rounding: A Technique for Provably Good Algorithms and Algorithmic Proofs", Combinatorica 7 (1987) 365	Prabhakar Raghavan, Clark D. Thompson	**307**	**20%**	**Design**

CAD Thrust
(UC Berkeley)

Google (VP of Engineering)

Basic Research on MOSFETs

Project started	Paper Title	Authors	Total Citations	Industry Percentage	Category
1992	"Measurement and modeling of self-heating in SOI NMOSFET's", IEEE TED 41 (1994) 69	Lisa T. Su, James, E. Chung, Dimitri Antoniadis, Ken Goodson, Markus Flik	**156**	**35%**	**Technology**

(MIT)

Lisa Su, a student who worked on an SRC research project with Dimitri Antoniadis, brought her experience to Texas Instruments, IBM (VP), Freescale (SVP & CTO) and AMD (President & CEO).

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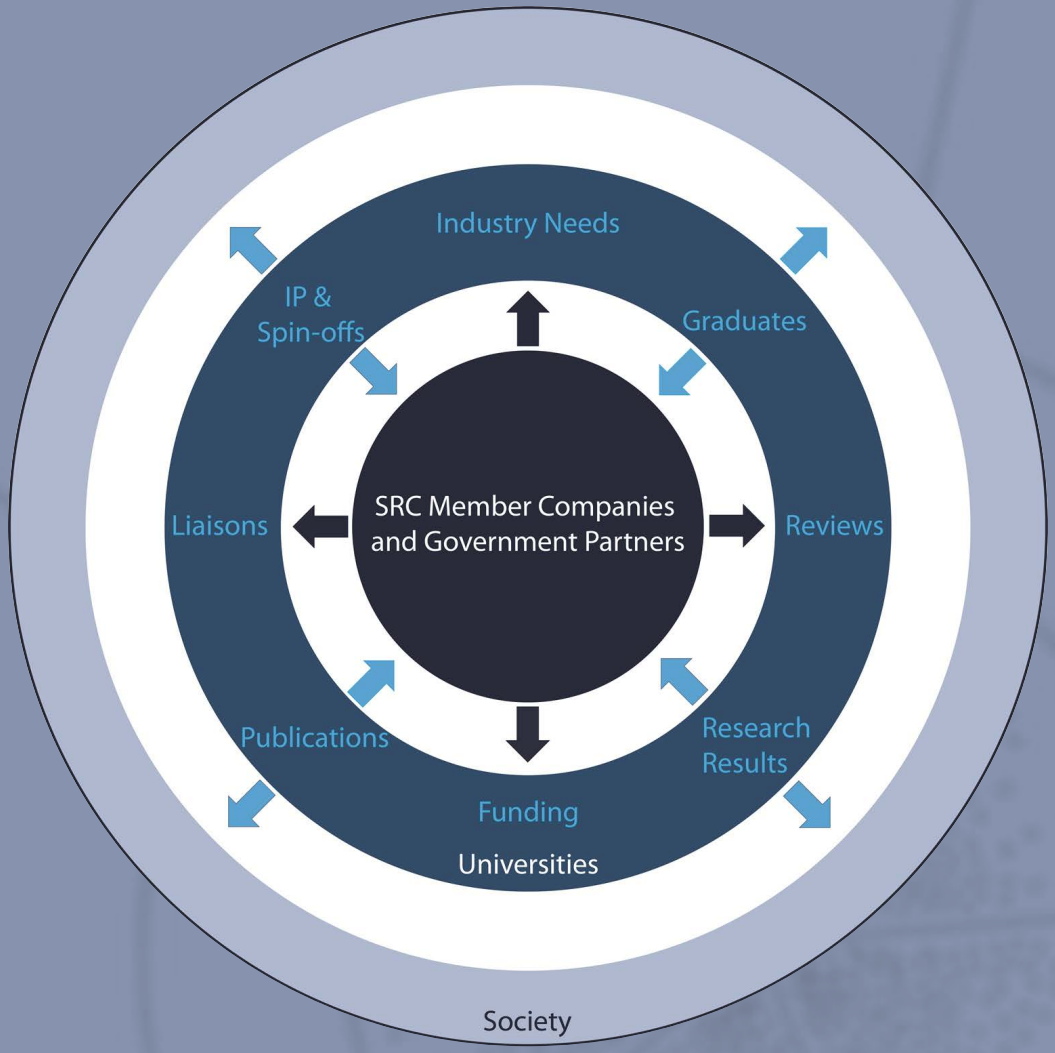
SRC Pathways for Collaboration

Knowledge creation for information technologies

This chart represents how SRC impacts, and is impacted by, its member companies. **SRC Member Companies and Government Partners** determine **Industry Needs**, provide **Funding** to **Universities,** monitor the research through regular **Reviews** and establish partnerships through Industrial **Liaisons**.

SRC Member Companies receive **Research Results**, relevantly educated and experienced **Graduates**, access to **Publications, Intellectual Property and Spin-offs**.

These outputs benefit the semiconductor industry, and **Society**, as a whole.



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Research Funding

- Enables steady stream of relevant concepts for industry
- Attracts outstanding students to semiconductor studies

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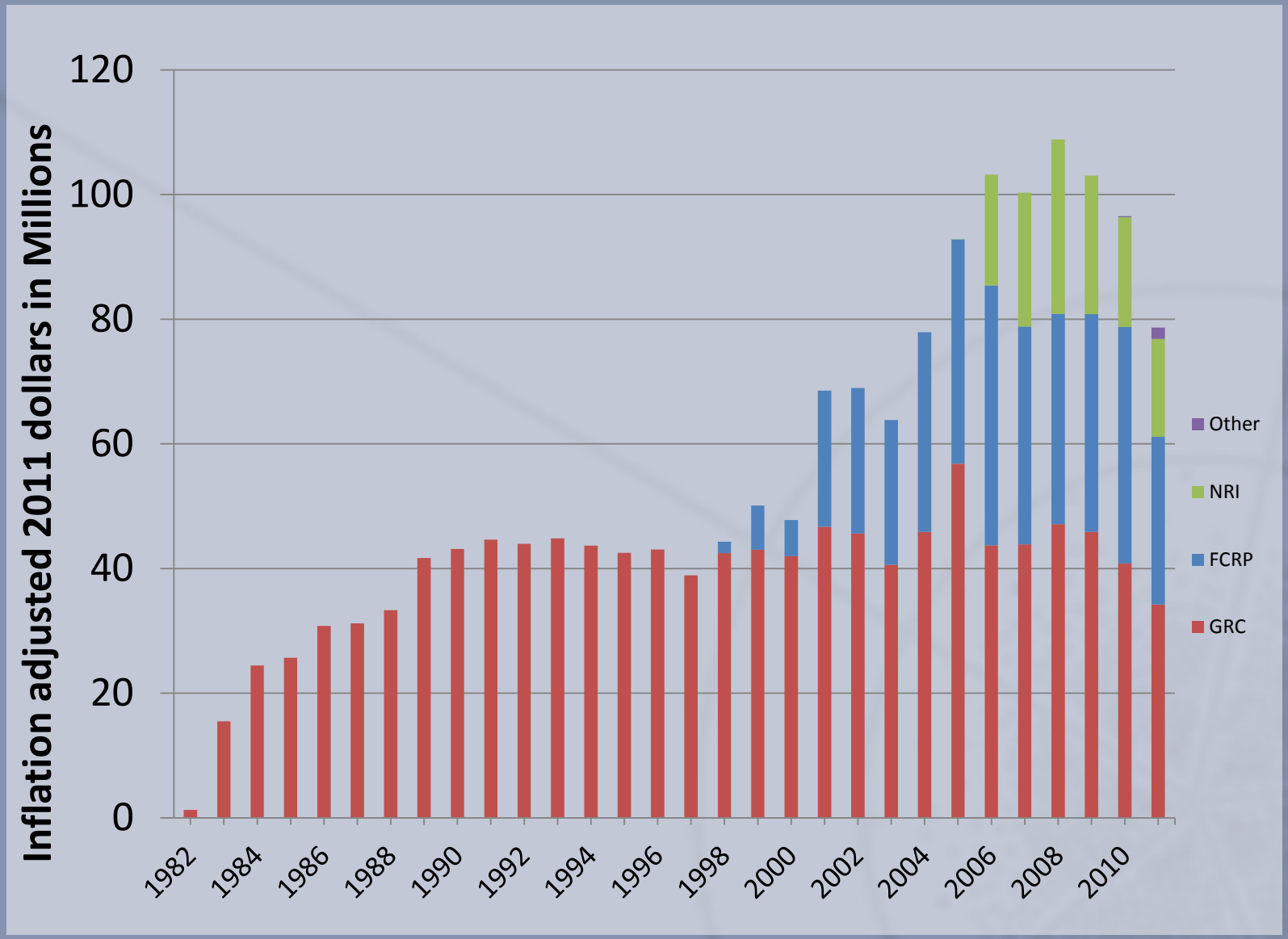
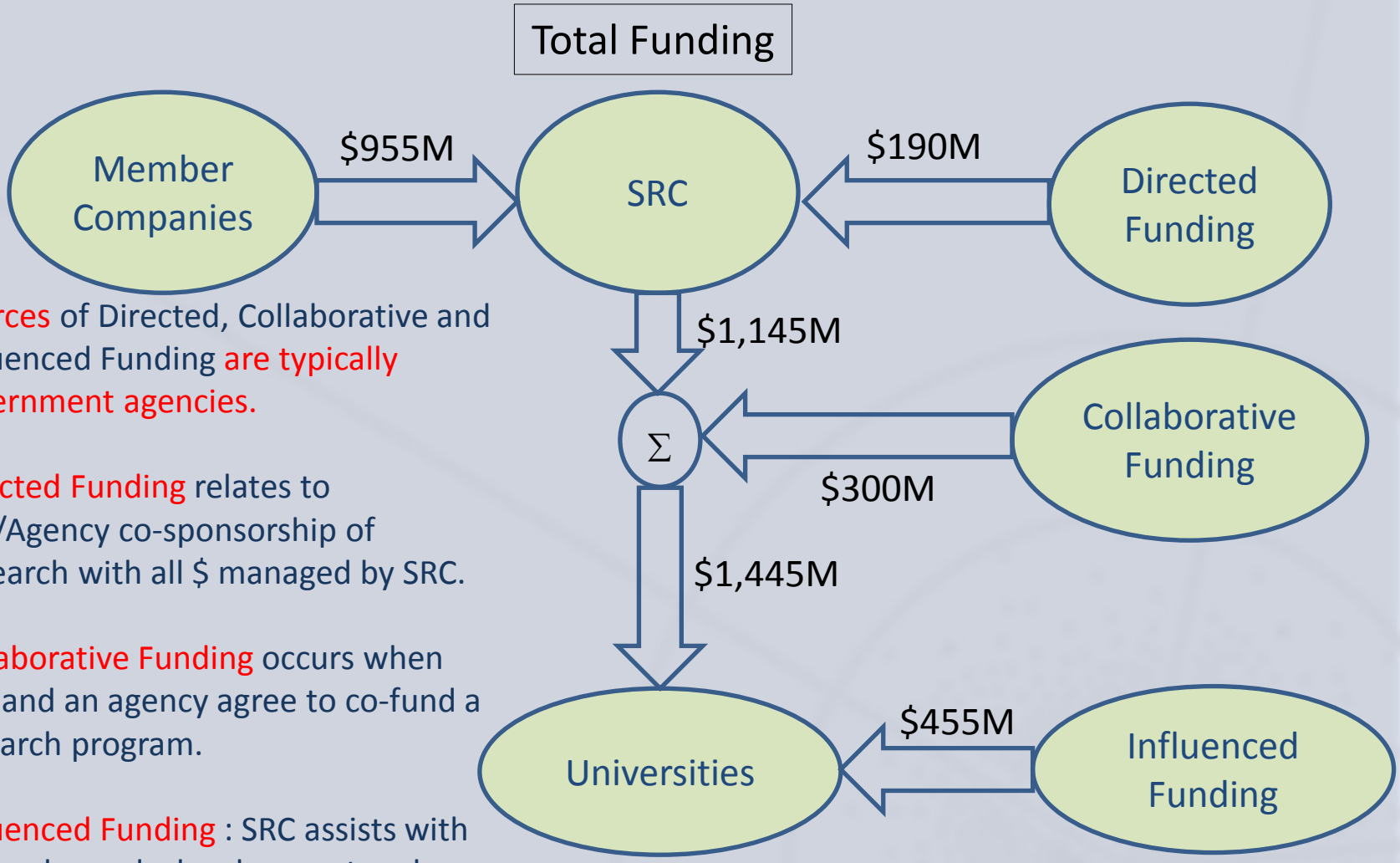
History of SRC Funding



SRC Funding Pathways – Actual $



- Sources of Directed, Collaborative and Influenced Funding are typically government agencies.
- Directed Funding relates to SRC/Agency co-sponsorship of Research with all $ managed by SRC.
- Collaborative Funding occurs when SRC and an agency agree to co-fund a research program.
- Influenced Funding : SRC assists with research needs development and proposal evaluations for government agencies and links subsequently funded projects to members.

Overall: $1.9B

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The SRC Research Agenda

How is it defined?

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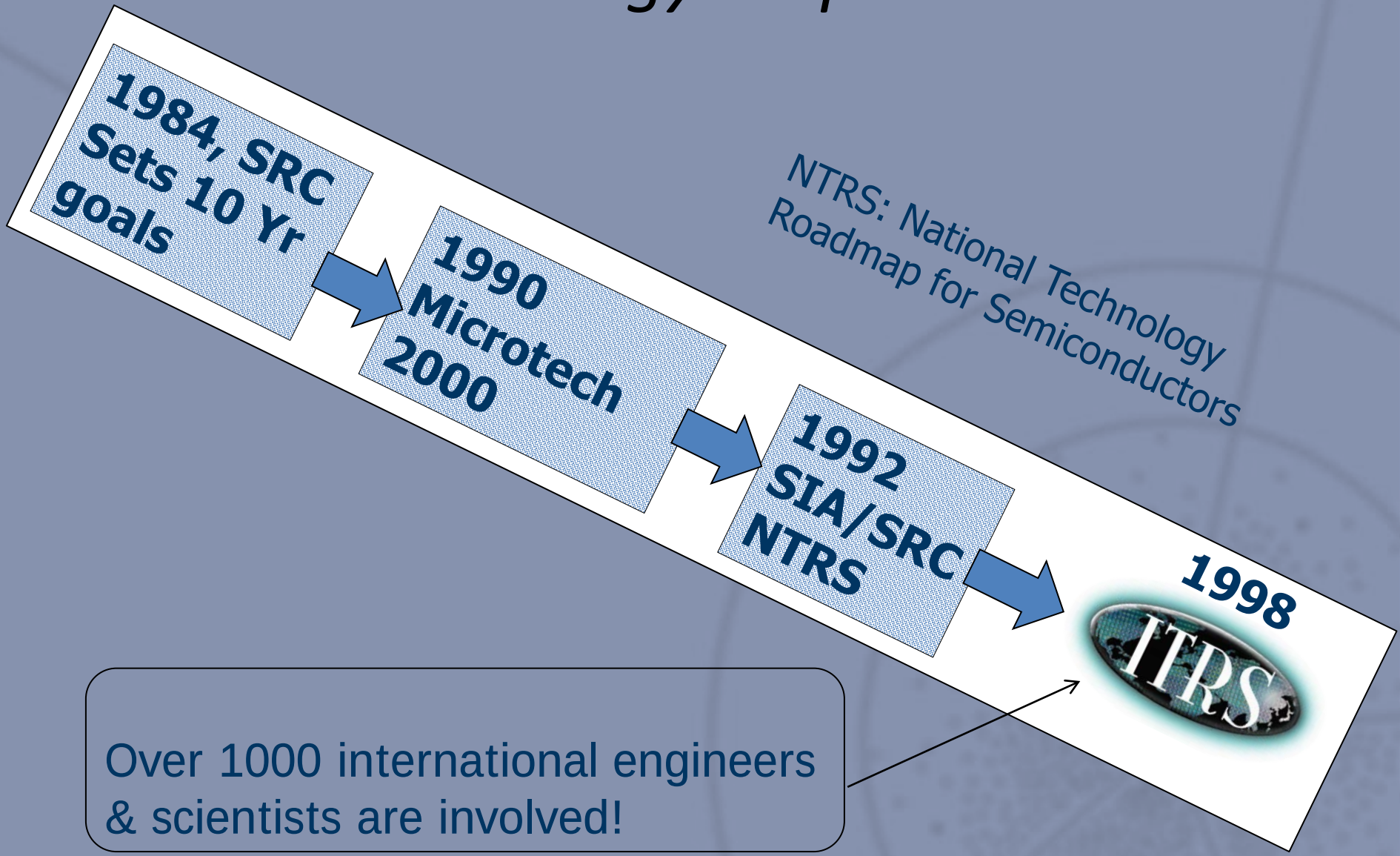
SRC Technical Advisory Boards

- Currently there are **1133** members of **Technical Advisory Boards** (TABs) who define research needs/review projects.
- There have been **1704** distinct TAB members across **52** different TABs throughout the SRC history.

Roadmapping: *15 Year Forecast for Technology Requirements*



Over 1000 international engineers & scientists are involved!

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Making the Partnership Real!

The Industrial Liaison Program

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Industrial Liaison Program

- SRC works to build **partnerships** between industry and the university.
- The Industrial Liaison Program is a key element:
  - Specialists from industry serve as **Friends of the Research.**
  - IL's can provide technical guidance, access to industry facilities for SRC research, serve on graduate committees, author joint papers, etc.
  - IL's are the frontline for **Technology Transfer, Student Recruiting.**

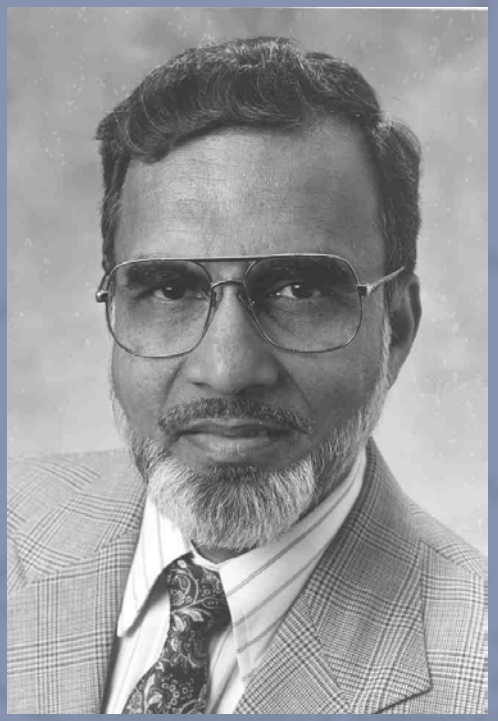
30 Years of Industrial Liaisons

- **3047** unique liaisons
- **2389** different research task assignments
- ~ **600** IL's are engaged in SRC research at any time.

- **Recognition of truly exceptional service is provided through the Mahboob Khan Award.**

The Mahboob Khan Award

Mahboob Khan of AMD set very high standards as an industry liaison. In his honor, the Award recognizes exceptional liaison performance.



Since it inception in 1997, 107 individuals have received the Mahboob Khan Award.

AMD

- Adam Pawloski (2005)
- David F. Reed (2000)
- Effiong Ibok (1998)
- Gamal Refai-Ahmed (2010)
- Linda Milor (1997)
- Paul Ferno (2010)
- Zoran Krivokapic (2006)

digital

- John Sauber (1997)

freescale

- Colin McAndrew (2007)
- Gary Morrison (2011)
- Hsi-An Kwong (2007, 2011)
- James Holt (2010)
- James (Skip) Egley (2004)
- Jayanta Bhadra (2011)
- Koneru Ramakrishna (2005)
- Magdy S. Abadir (2008)
- Martin Gall (2007)
- Matthew Miller (2009)
- Radu Secareanu (2007)
- Stefan Zollner (2008)
- Taras A. Kirichenko (2008)
- Willard Conley (2010)

*recipients are listed by employer at time of award

GLOBALFOUNDRIES

- Christian Witt (2009)
- Luigi Capodieci (2010)
- Todd Ryan (2011)

- Robert Aitken (1998)
- Ted Kamins (1997)

- Anne E. Gattiker (2008)
- Charles J. Alpert (2007, 2001)
- Chung-Hsun Lin (2011)
- Dan O'Connor (2006)
- Denise Puisto (1997)
- James Libous (2006, 2002)
- James Ryan (1999)
- Jason Baumgartner (2011)
- Phil Nigh (2005)
- Richard Williams (2011)
- Robert Allen (2000)
- Robert Gauthier (2006)
- Robert Rosenberg (2011, 2008)
- Ruchir Puri (2008)
- Sani Nassif (2006, 2004)
- Steven German (2004)

*recipients are listed by employer at time of award

- Ching Tsun Chou (2005)
- Dmitri Nikonov (2010)
- Henning Braunisch (2008)
- Hong Wang (2011)
- Jeff Bielefeld (2010)
- Jeffrey Parkhurst (2002)
- Kemal Aygun (2008)
- Mani Janakiram (2003, 1999)
- Martin Giles (1998, 1997)
- Michael Kishinevsky (2010, 2004)
- Mosur Mohan (2010)
- Prashant Sawkar (2000)
- Ram Kumar Krishnamurthy (2011, 2002)
- Sanu Mathew (2009)
- Shih-Lien Lu (2009)
- Susheel Jadhav (2005)

- T.M. Mak (2004, 1997)
- Timothy Kam (2004)
- Wilman Tsai(2009)

- Alexander Liddle (1998)
- Robert Kurshan (2001)
- Sungho Jin (1998)

- Andres Takach (2010)

*recipients are listed by employer at time of award

MOTOROLA

- Dejan Jovanovic (2001)
- Doug Garrity (2002)
- James (Skip) Egley (2004)
- Laurie Beu (1998)
- Pawitter Mangat (2003)
- Terry Sparks (2002)
- Will Conley (2003)

NOVELLUS

- George "Andy" Antonelli (2011)
- Jon Reid (2007)
- Larry Gochberg (2006, 2003)

SEMATECH

- Bradley Van Eck (1997)

National Semiconductor

- Hosam Haggag (2003)
- Luu Nguyen (2003)

Shipley Company

- Charles Szmanda (2002)

*recipients are listed by employer at time of award

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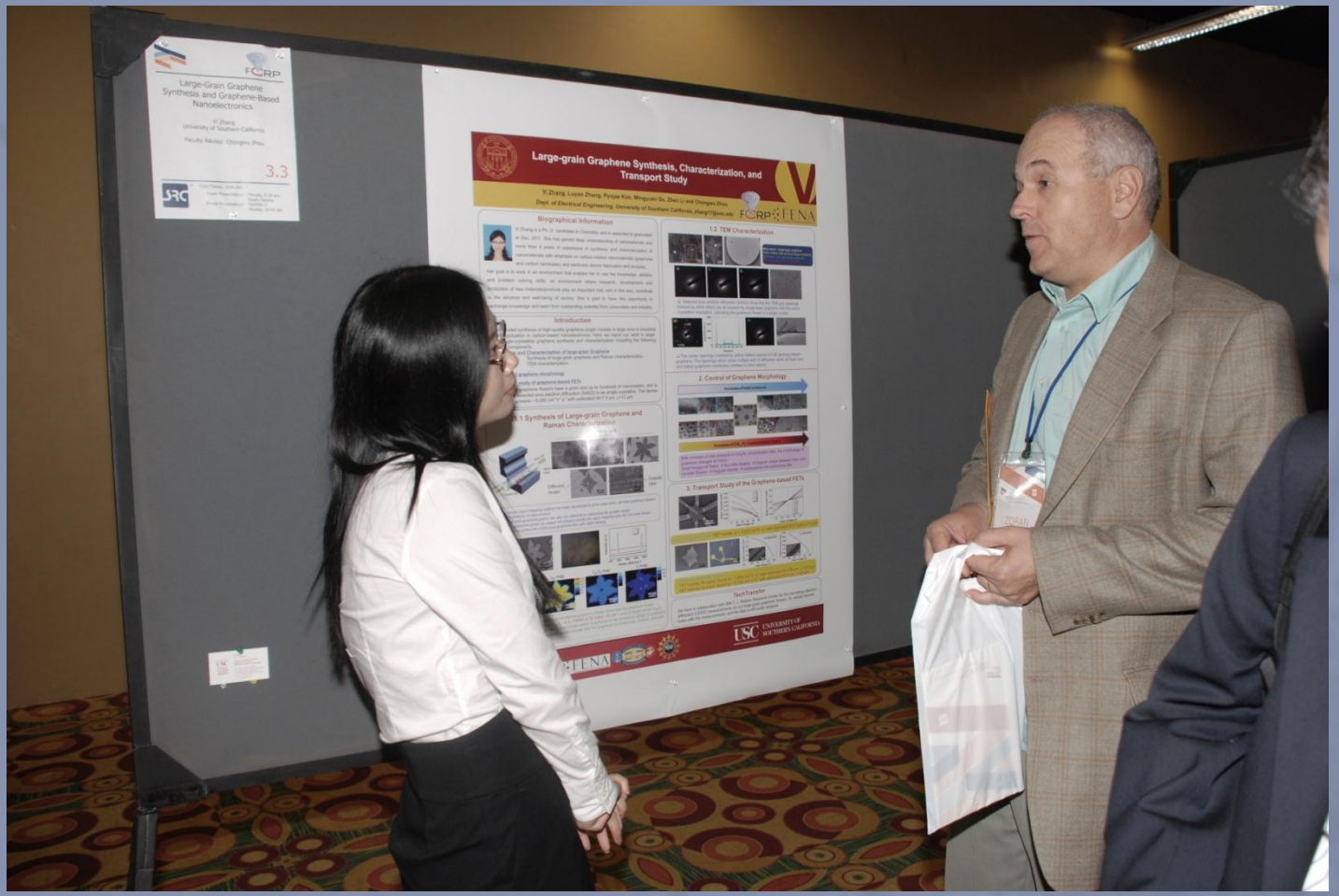
Texas Instruments

- Anand Krishnan (2010)
- Friedrich J. Taenzler (2008)
- Ganesh Srinivasan (2010)
- Jeff Zhao (2011)
- John Carulli (2010)
- Keith Green (2011, 2005)
- Ken Butler (2011, 2006)
- Marie Denison (2010)
- Mark Mason (2000)
- Mike Lamson (2005)
- Rick Wise (2010, 2007)
- Srikanth Krishnan (2010)
- Turker Kuyel (2003)
- Vijay Reddy (2011)

*recipients are listed by employer at time of award

Industry Feedback on Research



Constructive Assessments for Increased Effectiveness

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Research Reviews

- SRC Members take the responsibility of research monitoring very seriously and review every SRC research program every year.

- **~ 850** reviews since inception to strengthen research and the industry-university partnership

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Our University Partners

Acknowledging the Contributions of Faculty & Students in Support of the SRC Mission

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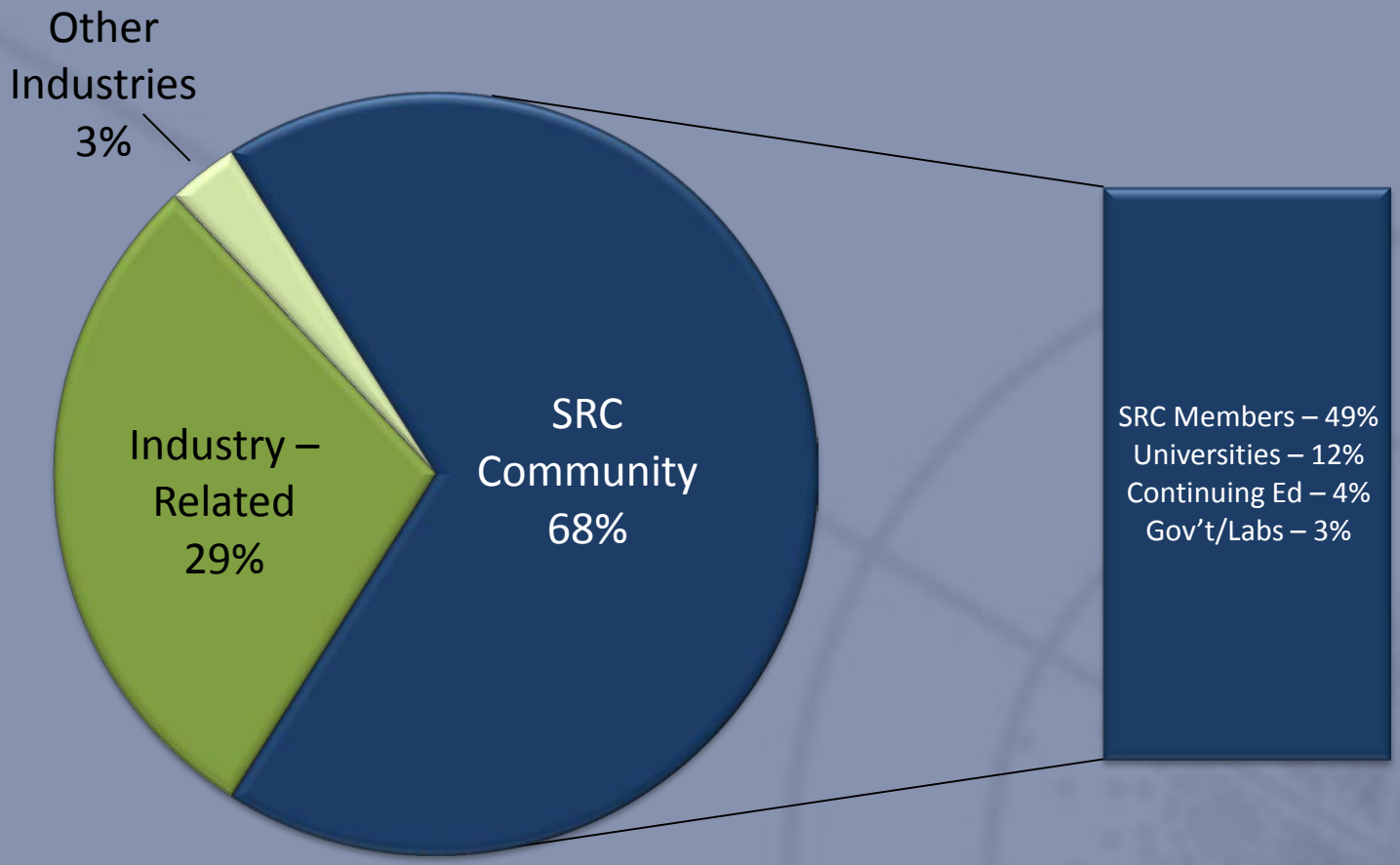
Graduates

- Since 1982, over **9400** students have worked on SRC sponsored projects.
- At any given time, there are between **1200** and **1500** students involved in SRC research.
- The vast majority of our alumni obtained graduate degrees, mostly the Ph.D.

SRC Graduates Begin Careers in the Community



Information reflects over 4200 graduates with known first hire data

Spotlight on SRC Alumni

Larry Pileggi - Professor and Head of ECE @ CMU
(AWE)

Tze-Chiang Chen -IBM VP, Science & Technology Research
(2011 IEEE Weber Prize)

Bing Sheu -TSMC Director of Design Platform
(BSIM)

More Former Students

Veena Misra,
Professor ECE, NCSU

Mary Ann Maher
CEO, SoftMEMS

Prith Bannerjee,
CTO, ABB

More Former Students

Bernhard Boser,
Professor of ECE,
UC Berkeley

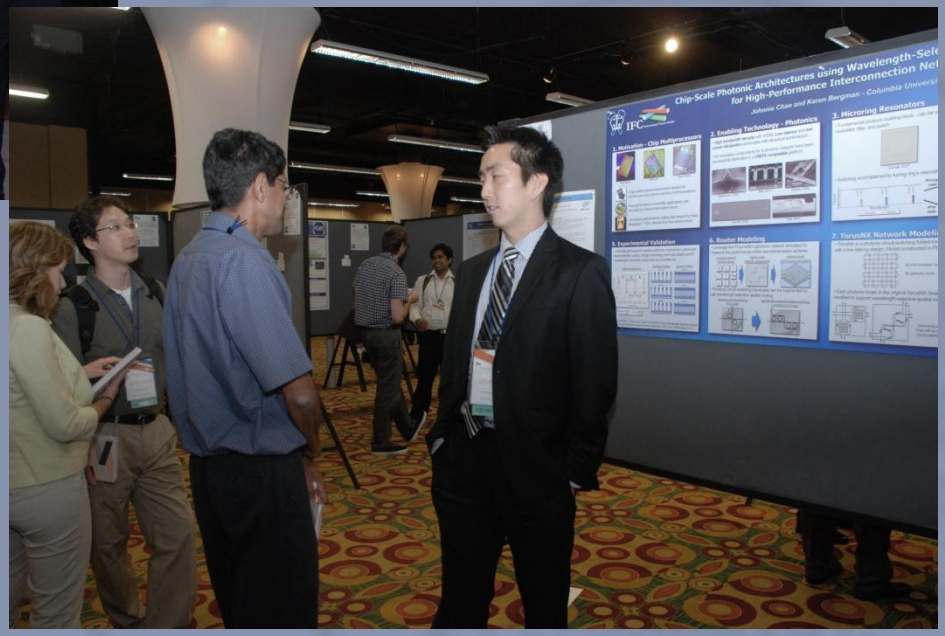
Kent Fuchs,
Provost, Cornell

And so many more!

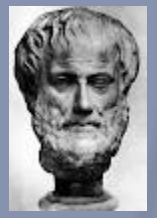
Collaboration is the Key!

TECHCON: A celebration of our students

“Let me show you my results!”

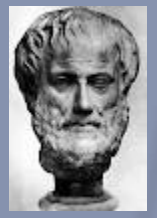


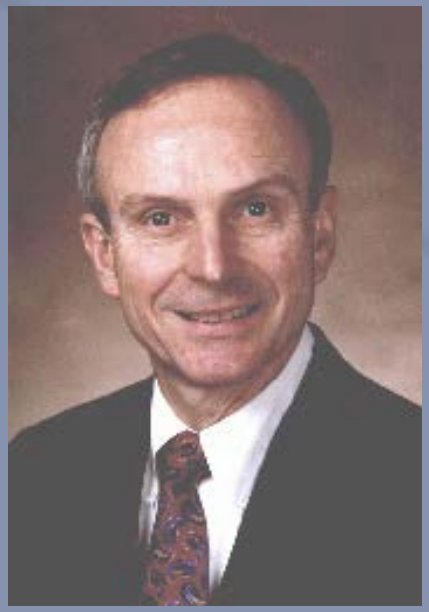
The SRC Aristotle Award



This is award recognizes career contributions of faculty who have distinguished careers in semiconductor research, in education, and in life-long mentoring of their students.

SRC Aristotle Awards



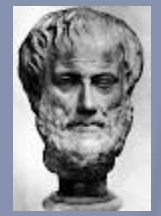


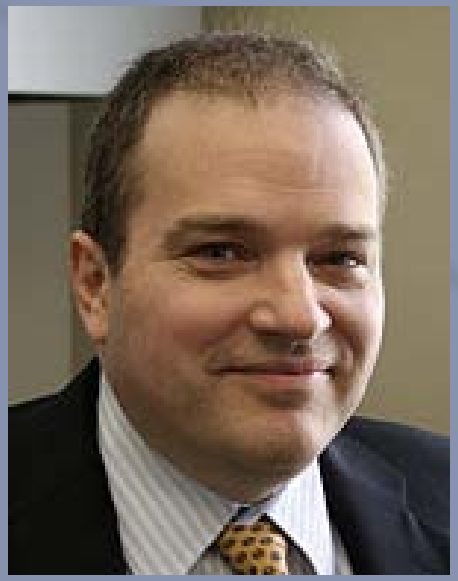
Bob Dutton
Stanford, 2011

Mark Lundstrom
Purdue, 2010

Chenming Hu
Berkeley, 2009

Aristotle Award Winners



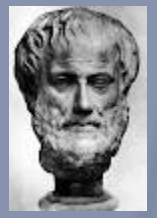


Larry Pileggi
CMU, 2008

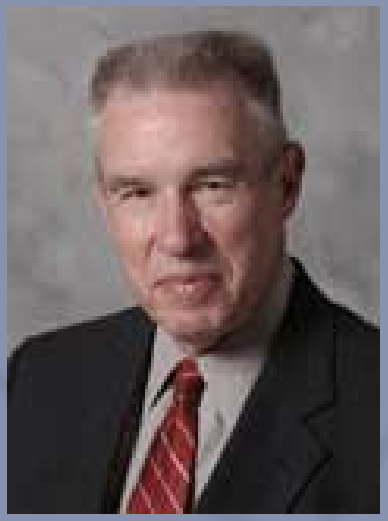
Wojceich Maly
CMU, 2007

Mark Law
U. FLA, 2006

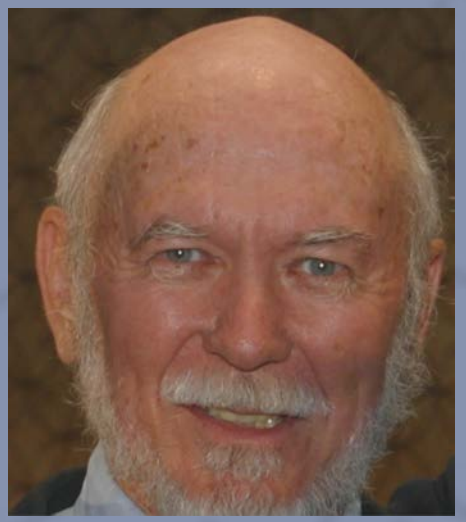
Aristotle Award Winners



David Allstot
U. Washington, 2005

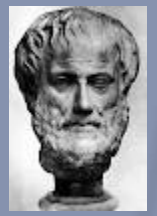


James Meindl
Georgia Tech, 2004



Jimmie Wortman
NCSU, 2003

Aristotle Award Winners

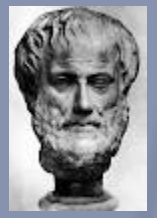


Alberto Sangiovanni-Vincentelli
UC Berkeley,2002

Rob Rutenbar
CMU, 2001

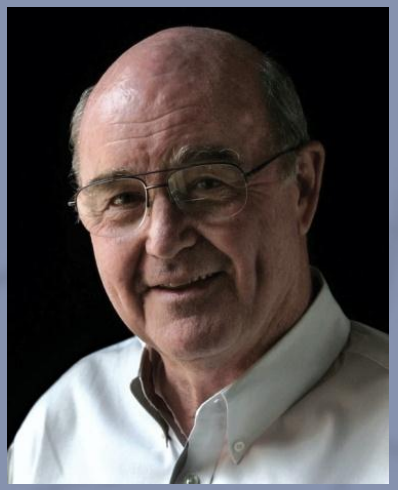
Gerald Neudeck
Purdue, 2001

Aristotle Award Winners



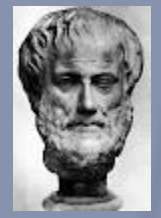
Rafael Reif
MIT, 2000

Roxann Englestad
U. Wisconsin, 1999



Grant Willson
U. TX, 1999

Aristotle Award Winners



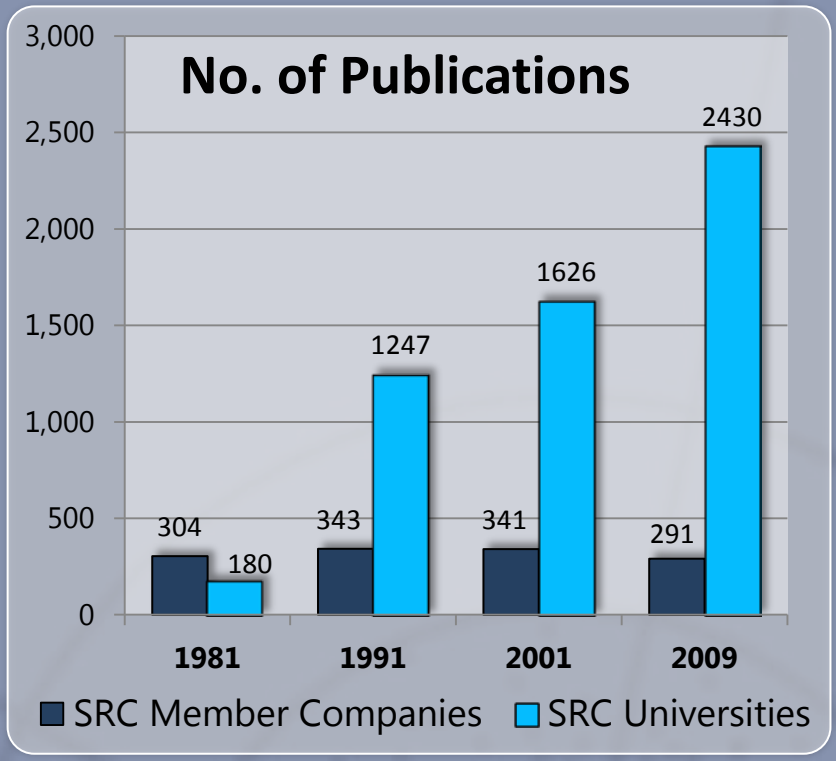
Franco Cerrina
U Wisconsin, 1998

Kensall Wise
U. Michigan, 1997

Stephen Director
CMU, 1996

Major Accomplishments

Built the world's largest and most successful university research force to support the 10,000-fold advances of the semiconductor industry.



- In 1982, less than 100 students and faculty conducted silicon research.
- In 2011, that number is **500 faculty** and **1,500 students**!

The SRC community publishes 20% of the world's research on silicon; seven times more than AMD, GLOBALFOUNDRIES, IBM, Intel, Freescale, and TI ***combined.***

Return to Outline

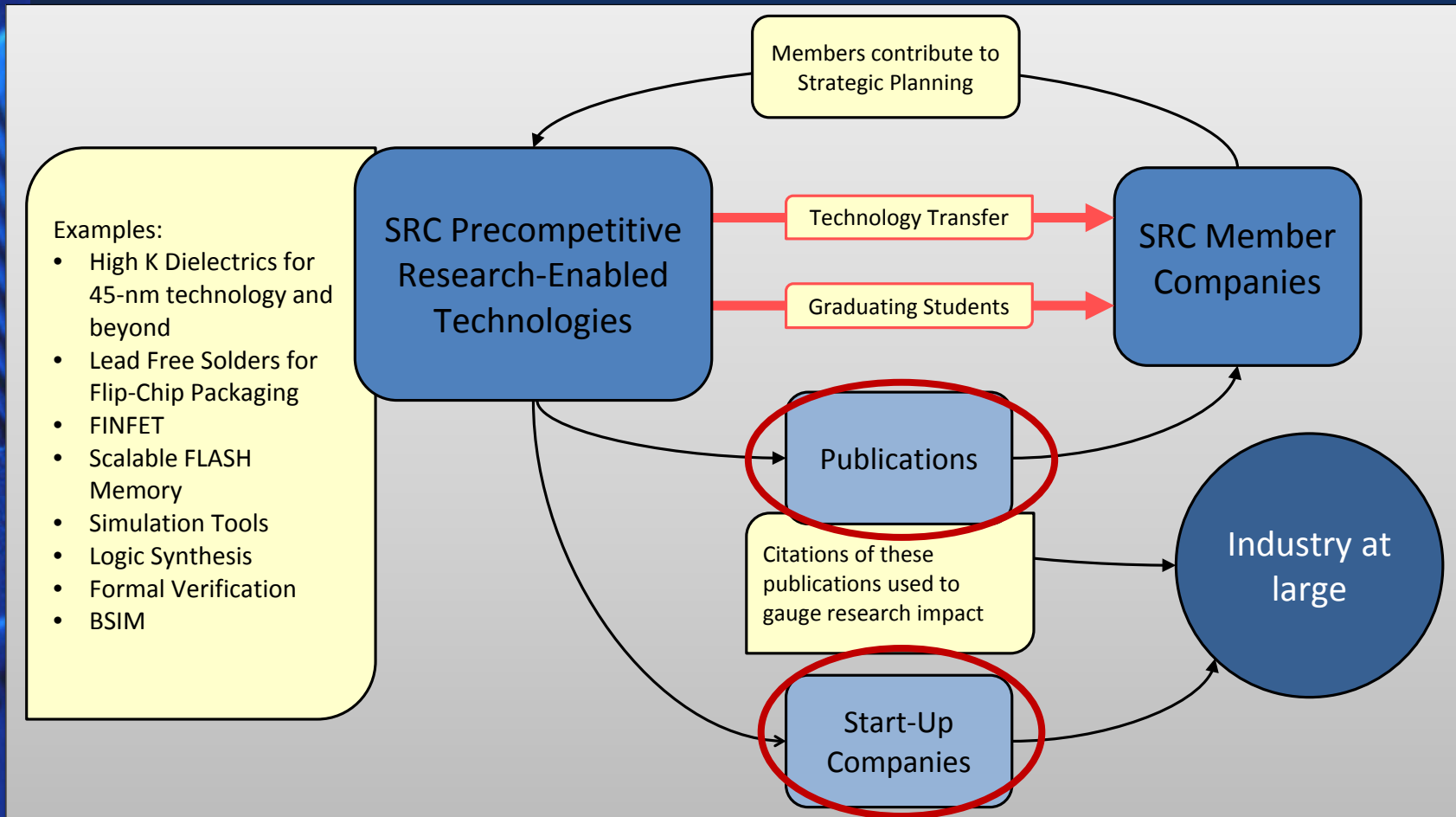
Impacting our Members

- Examples of Contributions to Member Company Workforce and Technology Infrastructure

Return to Outline

SRC Research: Designed for Impact

- SRC research anticipates future technology needs of members and provides results via timely and relevant technology transfer
- In addition, SRC research produces a significant number of influential papers and start up companies, which benefits the industry as a whole



Former SRC students and liaisons are developing new industry technologies

A 45nm Logic Technology with High-k+Metal Gate Transistors, Strained Silicon, 9 Cu Interconnect Layers, 193nm Dry Patterning, and 100% Pb-free Packaging

K. Mistry, C. Allen, C. Auth, B. Beattie, D. Bergstrom, M. Bost, M. Brazier, M. Buehler, A. Cappellani, R. Chau*, C.-H. Choi, G. Ding, K. Fischer, T. Ghani, R. Grover, W. Han, D. Hanken, M. Hattendorf, J. He#, J. Hicks#, R. Huessner, D. Ingerly, P. Jain, R. James, L. Jong, S. Joshi, C. Kenyon, K. Kuhn, K. Lee, H. Liu, J. Maiz#, B. McIntyre, P. Moon, J. Neirynck, S. Pae#, C. Parker, D. Parsons, C. Prasad#, L. Pipes, M. Prince, P. Ranade, T. Reynolds, J. Sandford, L. Shifren%, J. Sebastian, J. Seiple, D. Simon, S. Sivakumar, P. Smith, C. Thomas, T. Troeger, P. Vandervoorn, S. Williams, K. Zawadzki

Logic Technology Development, *Components Research, #QRE, %TCAD, Intel Corp., Hillsboro, OR, U.S.A.

7 SRC Alumni
5 SRC Liaisons
22% SRC participants

December 2007

IEEE iedm

Former SRC students, TAB members & Liaisons are developing new industry technologies

EUV Lithography at the 22-nm technology node

Obert Wood[a*], Chiew-Seng Koay[b], Karen Petrillo[b], Hiroyuki Mizuno[c], Sudhar Raghunathan[b], John Arnold[b], Dave Horak[b], Martin Burkhardt[d], Gregory Mcintyre[b], Yunfei Deng[e], Bruno La Fontaine[e], Uzo Okoroanyanwu[a], Tom Wallow[e], Guillaume Landie[f], Theodorus Standaert[b], Sean Burns[d], Christopher Waskiewicz[b], Hirohisa Kawasaki[c], James H.-C. Chen[b], Matthew Colburn[b], Bala Haran[b], Susan S.-C. Fan[b], Yunpeng Yin[b], Christian Holfeld[g], Jens Techel[g], Jan-Hendrik Peters[g], Sander Bouten[h], Brian Lee[h], Bill Pierson[h], Bart Kessels[h], Robert Routh[h], and Kevin Cummings[h]

[a]GLOBALFOUNDRIES, 257 Fuller Road, Albany, NY 12203 USA
[b]IBM Corporation, 257 Fuller Road, Albany, NY 12203 USA
[c]Toshiba America Electronic Components, 257 Fuller Road, Albany, NY 12203 USA
[d]IBM Corporation, 2070 Route 52, Hopewell Junction, NY 12533
[e]GLOBALFOUNDRIES, 1050 E. Arques, Sunnyvale, CA 94088
[f]STMicroelectronics, 257 Fuller Road, Albany, NY 12203 USA
[g]AMTC, Rahnitzer Allee 9, D-01109 Dresden, Germany
[h]ASML, 25 Corporate Circle, Albany, NY 12203 USA

7 SRC Alumni
6 SRC Liaisons
3 SRC TAB Participants
37.5% SRC participants

GLOBALFOUNDRIES

IBM

Former SRC students, TAB members & Liaisons are developing new industry technologies

A 32nm Logic Technology Featuring 2nd-Generation High-k + Metal-Gate Transistors, Enhanced Channel Strain and 0.171μm² SRAM Cell Size in a 291Mb Array

S. Natarajan, M. Armstrong, M. Bost, R. Brain, M. Brazier, C-H Chang, V. Chikarmane, M. Childs, H. Deshpande, K. Dev, G. Ding, T. Ghani, O. Golonzka, W. Han, J. He*, R. Heussner, R. James, I. Jin, C. Kenyon, S. Klopcic, S-H. Lee, M. Liu, S. Lodha, B. McFadden, A. Murthy, L. Neiberg, J. Neirynck, P. Packan, S. Pae*, C. Parker, C. Pelto, L. Pipes, J. Sebastian, J. Seiple, B. Sell, S. Sivakumar, B. Song, K. Tone, T. Troeger, C. Weber**, M. Yang, A. Yeoh, K. Zhang
Logic Technology Development, * Quality and Reliability Engineering, ** TCAD, Intel Corporation.
Phone: (503) 613-8029; Email: sanjay.natarajan@intel.com

6 SRC Alumni
6 Liaisons
1 TAB Member
26.7% SRC Participants

December 2008
IEEE iedm

RF CMOS Technology Scaling in High-k/Metal Gate Era for RF SoC (System-on-Chip) Applications

C.-H. Jan, M. Agostinelli, H. Deshpande, M. A. El-Tanani, W. Hafez, U. Jalan, L. Janbay, M. Kang, H. Lakdawala*, J. Lin, Y-L Lu, S. Mudanai, J. Park, A. Rahman, J. Rizk, W.-K. Shin, K. Soumyanath*, H. Tashiro, C. Tsai, P. VanDerVoorn, J.-Y. Yeh, P. Bai

Logic Technology Development (LTD), Intel Corporation, Hillsboro, Oregon, USA
*Integrated Platform Research/Radio Integration Research (RIR), Intel Labs, Intel Corporation, Hillsboro, Oregon, USA
Contact: e-mail chia-hong.jan@intel.com

December 2010
IEEE iedm

8 SRC Graduated Students
7 Liaisons
4 TAB Advisors
54.5% SRC Participants

Survey Paper

Automatic control in microelectronics manufacturing: Practices, challenges, and possibilities☆

Thomas F. Edgar[a,*], Stephanie W. Butler[b], W. Jarrett Campbell[c,1], Carlos Pfeiffer[d], Christopher Bode[c], Sung Bo Hwang[e], K. S. Balakrishnan[d], J. Hahn[a]

[a]*Department of Chemical Engineering, The University of Texas, Austin, TX 78712, USA*
[b]*Texas Instruments, Dallas, TX, USA*
[c]*Advanced Micro Devices, Austin, TX, USA*
[d]*Motorola, Austin, TX, USA*
[e]*Hyundai, Ichon, South Korea*

Received 28 May 1998; revised 9 April 1999; received in final form 28 August 1999

Liaison/TAB Member

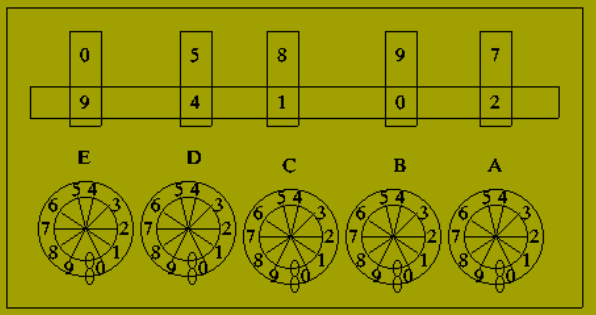
This publication cites **16**
SRC sponsored articles as references

TEXAS INSTRUMENTS

AMD

Compelling Reasons for SRC Membership

- ***Compelling reason:*** Innovative SRC research of extraordinary benefit to a member company.
  - A **compelling reason** should be so evident that it could be described to the CEO on an elevator ride.
  - We have received from our members literally thousands of compelling reasons over the last fifteen years.
  - SRC research has accelerated company technologies and provided millions of dollars in cost savings.



Front Panel of Pascal's Calculator

Blaise Pascal, circa 1600
An innovator slightly ahead of his time!

Return to Outline

Celebrating Accomplishments

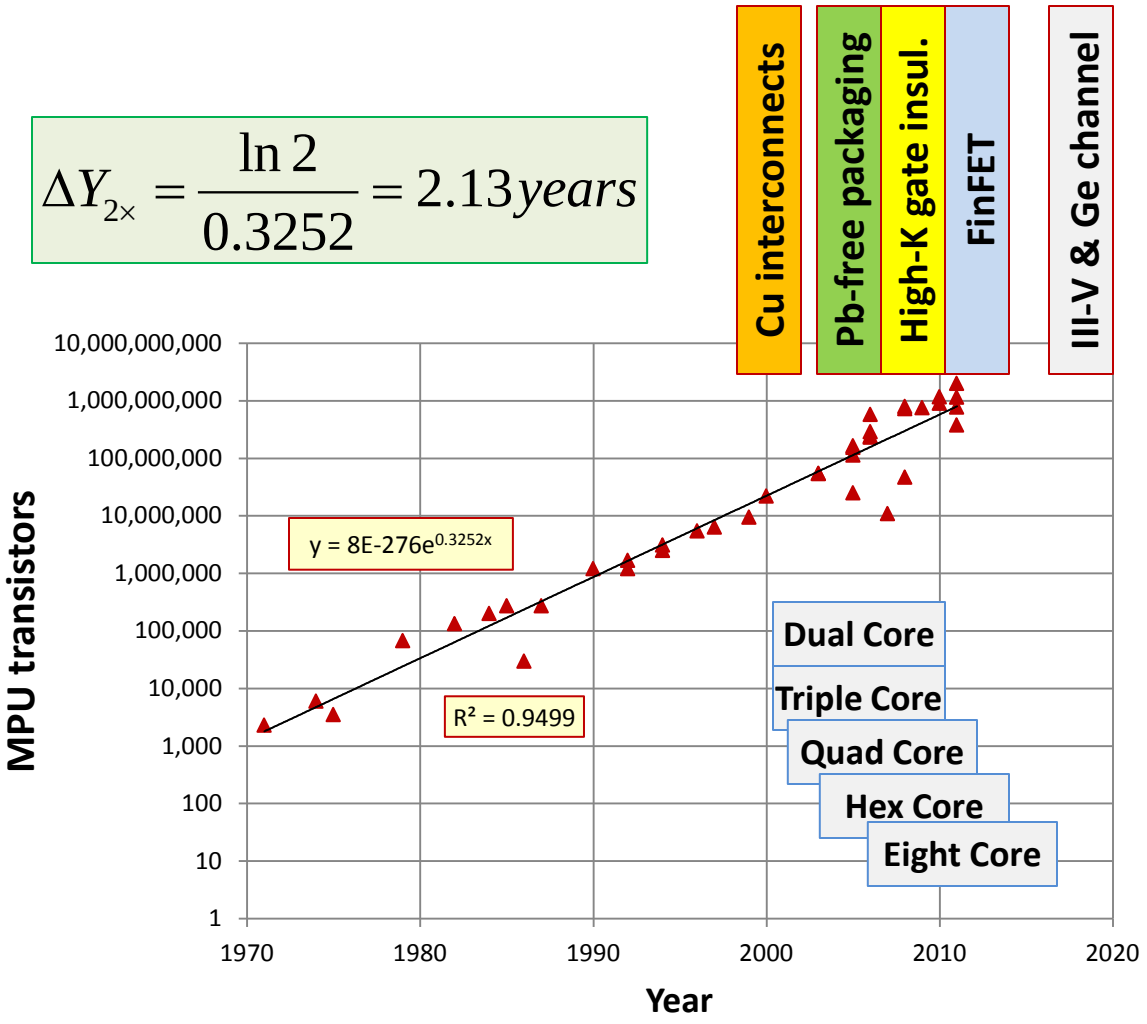
A few examples of research contributing to our members' technologies

- **The Copper Revolution**
- **The high-K Breakthrough**
- **'Green' Flip-Chip Packages**
- **Birth of the CAD Industry**
- **Compact Modeling**
- **Flash Memory**
- **Simulation tools (Process, Device, Circuit, System)**
- **Logic Synthesis**
- **Formal Verification**
- **Many more**

Return to Outline

Moore's Law: 1971-2011 (Microprocessors)

$$\Delta Y_{2\times} = \frac{\ln 2}{0.3252} = 2.13 years$$



Company	Model	Year
Intel	4004	1971
Intel	8080	1974
MOS Technology	6502	1975
Motorola 68000	68000	1979
Intel	286	1982
Motorola	68020	1984
Intel	386DX	1985
ARM	ARM2	1986
Motorola	68030	1987
Motorola	68040	1990
DEC	Alpha 21064 EV4	1992
Intel	486DX	1992
Motorola	68060	1994
Intel	Pentium	1994
Intel	Pentium Pro	1996
IBM - Motorola	PowerPC 750	1997
Intel	Pentium III	1999
AMD	Athlon	2000
AMD	Athlon XP 2500+	2003
Intel	Pentium 4 Ext. Edition	2003
Centaur - VIA	VIA C7	2005
AMD	Athlon FX-57	2005
AMD	Athlon 64 3800+ X2	2005
IBM	Xbox360 "Xenon"	2005
Sony-Toshiba-IBM	PS3 Cell BE	2006
AMD	Athlon FX-60	2006
Intel	Core 2 Extreme X6800	2006
Intel	Core 2 Extreme QX6700	2006
P.A. Semi	PA6T-1682M	2007
Intel	Core 2 Extreme QX9770	2008
Intel	Core i7 920	2008
Intel	Atom N270	2008
AMD	E-350	2011
AMD	Phenom II X4 940	2009
AMD	Phenom II X6 1100T	2010
Intel	Core i7 980X	2010
Intel	Core i7 2600K	2011
Intel	Core i7 875K	2011
AMD	8150	2011

The Copper Revolution

Research Start: 1989

~10 years

Cornell, Berkeley, RPI, SUNY Albany

Commercialization: 1998-2002

Need:

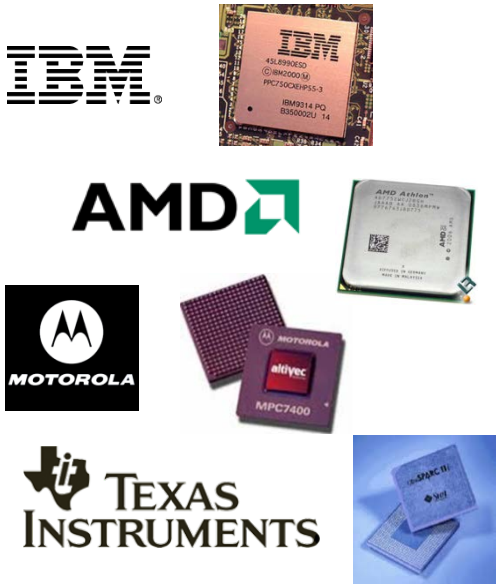
Interconnects to:

1) break the **1GHz** barrier

2) reduce power

Challenge: Replace Al with Cu

- New deposition process
- Reliability (e.g. Cu diffusion and electromigration)



15 SRC-supported influential publications

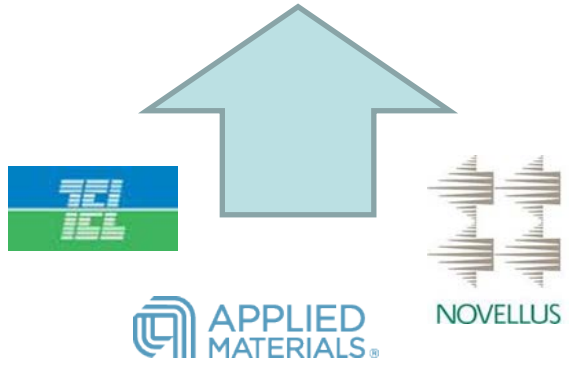
Early (1993) SRC papers on Cu interconnects:

- Y. Shacham-Diamand et al, "**Copper Transport in Thermal SiO_2**", J. Electrochem Soc. 140 (1993) 2427

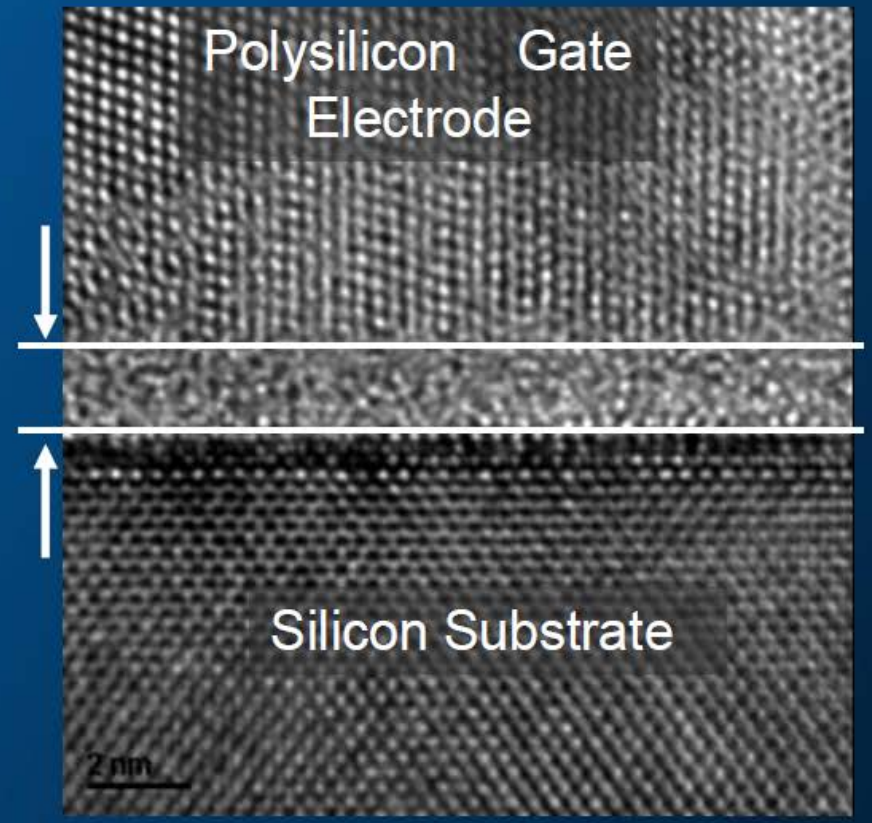
  124 citations; 33% by industry

- S. P. Murarka et al, "**Advanced multilayer metallization schemes with copper as interconnection metal**", Thin Solid Films 236 (1993) 257

  197citations; 26% by industry



"We're running out of atoms"



1.2 nm SiO_2

3-4 atoms thick

The Gate Dielectric Dilemma: Transistors are leaky & dissipate power, even when off!

Mike Mayberry, Intel Corp.

The high-K Breakthrough

Research Start: 1997

~11 years

Commercialization: 2008-2012

UT Austin, NCSU, U N-Texas, U S-Florida…

Need:

to address the "Running out of Atoms" crisis

Challenge:

Replacing SiO2 with high-K gate materials

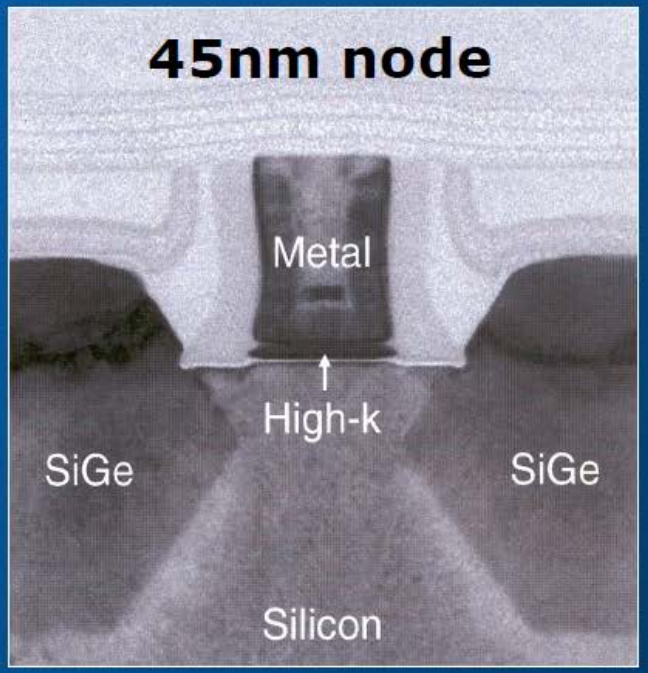
- New deposition process
- Gate metal etc.

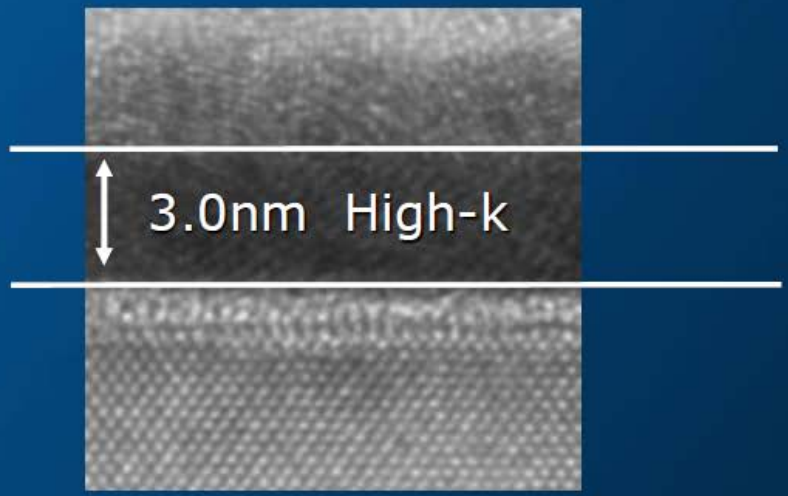
IBM, intel, AMD, Texas Instruments, freescale, GLOBALFOUNDRIES

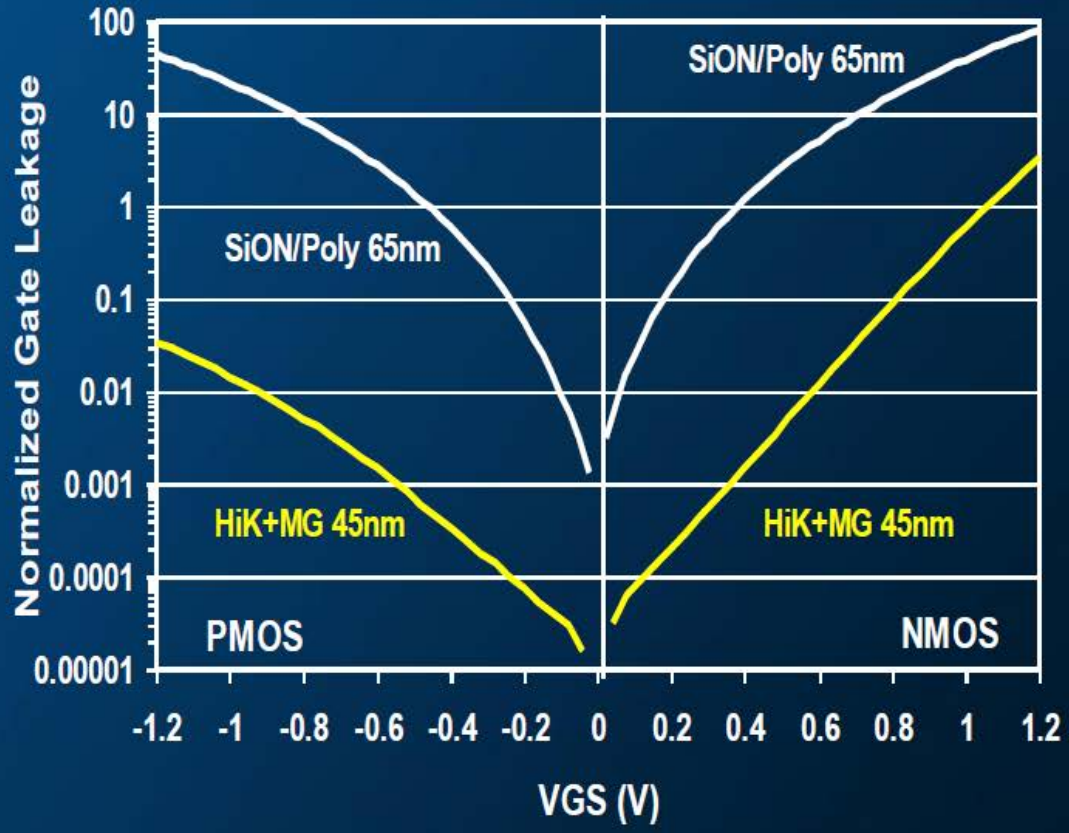
- Innovation of high-K gate dielectrics for use 45nm and beyond technology
- Successful transfer of high-K technology to industry.
- **18** SRC-supported influential publications (>100 citations)

Paper Title	Authors	Total Citations	Industry Percentage
High-k gate dielectrics: Current status and materials properties considerations, JAP 89 (**2001**) 5243	Wilk / Agere, Wallace /U. N Texas, Anthony/ U. S Florida	**3288**	**27%**
High quality ultra thin CVD HfO2 gate stack with poly-Si gate electrode, IEDM **2000**, 31-34	Dim Lee Kwong et al. /UT Austin	**126**	**34%**
Alternative dielectrics to silicon dioxide for memory and logic devices, Nature 406 (**2000**) 1032	Angus Kingon et al. / NCSU	**663**	**24%**

The Solution:
New Materials and New Fabrication







45 nm HK+MG provides >25x gate leakage reduction

Mike Mayberry, Intel Corp

‘Green’ Flip-Chip Packages

Research Start: 1993

12 years

Commercialization: ~2005

Prof. King-Ning Tu / UCLA

Texas Instruments

Discussion of a ban within the EU on products sold containing Pb to begin in 2006

Replacing the Tin-Lead alloy within Flip Chip Packaging

- Pb-free solders
- Reliability (e.g. Whisker Growth)

- Innovation of a “Green” flip chip for use in consumer electronics applications.
- Successful transfer of Pb-free packaging to industry.
- 9 SRC-supported influential publications (>100 citations)
- **World-record # of citations for paper on packaging:**
  - K. Zeng and K. N. Tu, "Six cases of reliability study of Pb-free solder joints in electronic packaging technology", MATERIALS SCIENCE & ENGINEERING 38 (2002) 55-105
- ***578 citations; ~20% by industry***

The Birth of CAD Industry

Berkeley, CMU

THE NEED for Design Automation

Compact Modeling Tools;
Formal Verification Tools;
Logic Synthesis Tools;
Simulation Tools

Mentor Graphics

cadence™

SYNOPSYS®
Predictable Success

- Original developments in Design Automation
- Successful transfer of CAD projects to industry.
- **15 SRC influential publications (>100 citations)**

1986	"Graph-based algorithms for Boolean function manipulation", *IEEE Trans on Comput* 35 (1986) 677	Bryant (CMU)	1754	321	18%
1987	"MIS: A Multiple-Level Logic Optimization System", IEEE Trans. CAD 6 (1987) 1062	R. K. Brayton, (UC/Berkeley)	261	89	34%
1987	"BSIM - Berkeley Short-Channel IGFET Model for MOS-Transistors", IEEE J. S-State Cir 22 (1987) 558	Sheu BJ et al (Berkeley U)	200	55	28%
1987	"Randomized Rounding: A Technique for Provably Good Algorithms and Algorithmic Proofs", Combinatorica 7 (1987) 365	Prabhakar Raghavan, C. D. Thompson	307	61	20%
1987	"Multiple-valued minimization for PLA Optimization", IEEE Trans. CAD 6 (1987) 727	A. Sangiovanni-Vincentelli, (UC/Berkeley)	106	15	14%
1989	"OASYS: A Framework for Analog Circuit Synthesis"	L. R. Carley, (CMU)	126	15	12%
1990	"Asymptotic waveform evaluation for timing analysis", IEEE Trans CAD 9 (1990) 352	R. A. Rohrer (CMU)	762	206	27%

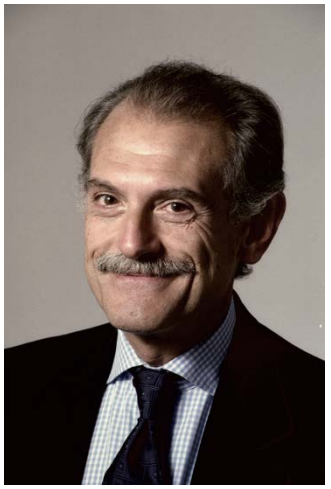
Design Automation

1986 SYNOPSYS® Predictable Success

1988 cadence™

Alberto Sangiovanni-Vincentelli, Co-Founder

SRC faculty researcher since 1982 working Logic Synthesis, High-level modeling, Simulation etc.



SRC-supported Research Helped to Make Possible Scalable Flash Memory

Hot-electron injection in thin films of insulators

To make a reliable and small FLASH memory with **very high capacity**, it was necessary to understand the physics of hot-electron injection in thin films of insulators.

The physics of hot-electron injection in thin insulator films was understood in 1989-1994 from basic research at Berkeley supported by SRC.

Paper Title	Authors	Total Citations	Industry Percentage
"Hole injection SiO2 breakdown model for very-low voltage lifetime extrapolation", IEEE Trans Electron Dev 41 (1994) 761	Klaus Schuegraf and Chenming Hu	**278**	**41%**

Klaus Schuegraf, CTO
Applied Materials

This basic research has enabled today's digital cameras, pocket memory sticks, iPod nano etc.

An SRC Tradition: Support for Compact Model Research

Need: Accurate and parsimonious models for chip circuit simulators

Challenge: Must be adaptable for a changing technology landscape

Importance: Compact Models are heavily used in chip design

SRC research in Compact Modeling began in mid-1980's and continues in 2012.

Berkeley BSIM Group

Return to Outline

SRC IP and Start Ups with SRC Roots

Return to Outline

Design Automation Companies with Roots in SRC Research

1992 — **Performance Signal Integrity** → **1994** — **Integrated Silicon Systems** → **1995** — Avant! → **2002** — **Acquired by Synopsis for ~$777M**

Timing Simulation

Co-founder: Eric Bracken — Carnegie Mellon University

1993 — **BTA Technologies** → **2001** — celestry → **2002** — **Acquired by Cadence for >$100M**

EDA tools for sub-μm scale semiconductor chips

Chengmin Hu founding chairman
Zhihong Liu, co-founder — Berkeley University of California

1996 — **OPC Technology** → **1998** — **Acquired by Mentor Graphics**

Software for resolution enhancement in optical lithography

Co-founders: Avideh Zakhor and Nick Cobb — Berkeley University of California

Design Automation Companies with Roots in SRC Research

2004 **2006**

CommandCAD → **Acquired by Cadence**

Design For Manufacturability

Co-founders: Frank Gennari, Greg McIntyre, Michael Lam,

Berkeley University of California

2004 **2011**

EXTREME DA → **Acquired by Synopsis**

Variation-aware optimization of IC designs

Yuji Kukimoto, Chief Scientist and Founder Berkeley University of California

Design for Manufacturing

1991

PDF SOLUTIONS®

Software for process control, yield simulators, engineering data analysis

Co-founders: John K. Kibarian, Andrzej Strojwas, Kimon Michaels — Carnegie Mellon University

2004

Fabbrix

Manufacturing yields

Founder: Larry Pileggi — Carnegie Mellon University

2007

Acquired by PDF Solutions for ~$6M

2004

BLAZE

Design for manufacturing

Co-founder: Andrew Kahng — UCSanDiego

2009

Acquired by Tela Innovations

Analog/Mixed Signal Companies with Roots in SRC Research

1991

Berkeley Design Technology, Inc.

DSP solutions

Edward A. Lee, Founder Berkeley University of California

1998

ATHEROS® COMMUNICATIONS

Wireless products

Teresa H. Meng
Founder and Director

2004

Timing, clock, and RF chips

Bernhard Boser
Co-Founder, Chief Scientist

2005

Fabless IC design company for wireless multimedia

Kanyu "Mark" Cao
Co-Founder and Vice President of Operations

Companies with Roots in SRC Research

1996 — **2004**

Acquired by Cadence for ~$100M

Analog synthesis

Founders: Ron Rutenbar and Richard Carley

Carnegie Mellon University

1998 — **2006**

Acquired by SanDisk for ~$200M

3-D IC

Vivek Subramanian, co-founder

Berkeley
University of California

2006 — **2011**

Acquired by Xilinx

High level synthesis for FPGAs and ASICs

Jason Cong, co-founder

UCLA

Process-related Companies with Roots in SRC Research

1999

Panoramic Technology

Lithography simulation software

Tom Pistor, Founder — Berkeley University of California

2007

inpria

Advanced Resists

Co-founder: Andrew Grenville

STANFORD UNIVERSITY

2009

NANOSONIX

Metrology of buried surfaces

Founder: Arvind Srivastava

NORTHWESTERN UNIVERSITY

2000

ONWAFER TECHNOLOGIES

Process Diagnostics Metrology

Mason Freed, Co-Founder and Vice President

Berkeley University of California

2007

Acquired by KLA-Tencor

Process-related Companies with Roots in SRC Research

2001

Molecular Imprints

Imprint lithography

Co-Founder: Grant Willson

THE UNIVERSITY OF TEXAS AT AUSTIN

2003

EMC
Environmental Metrology Corporation

Electrochemical Residue Sensors

Co-Founders: Farhang Shadman, Bert Vermeire

THE UNIVERSITY OF ARIZONA

2007

ARBOR PHOTONICS

EUV Source

Co-founder: Almantas Galvanauskas

UNIVERSITY OF MICHIGAN

Companies with Roots in SRC Research

1990

Sunrise Test Systems

Test automation solutions

Thomas Niermann

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

2002

POSEIDON
Design Systems

System Level Design

2008

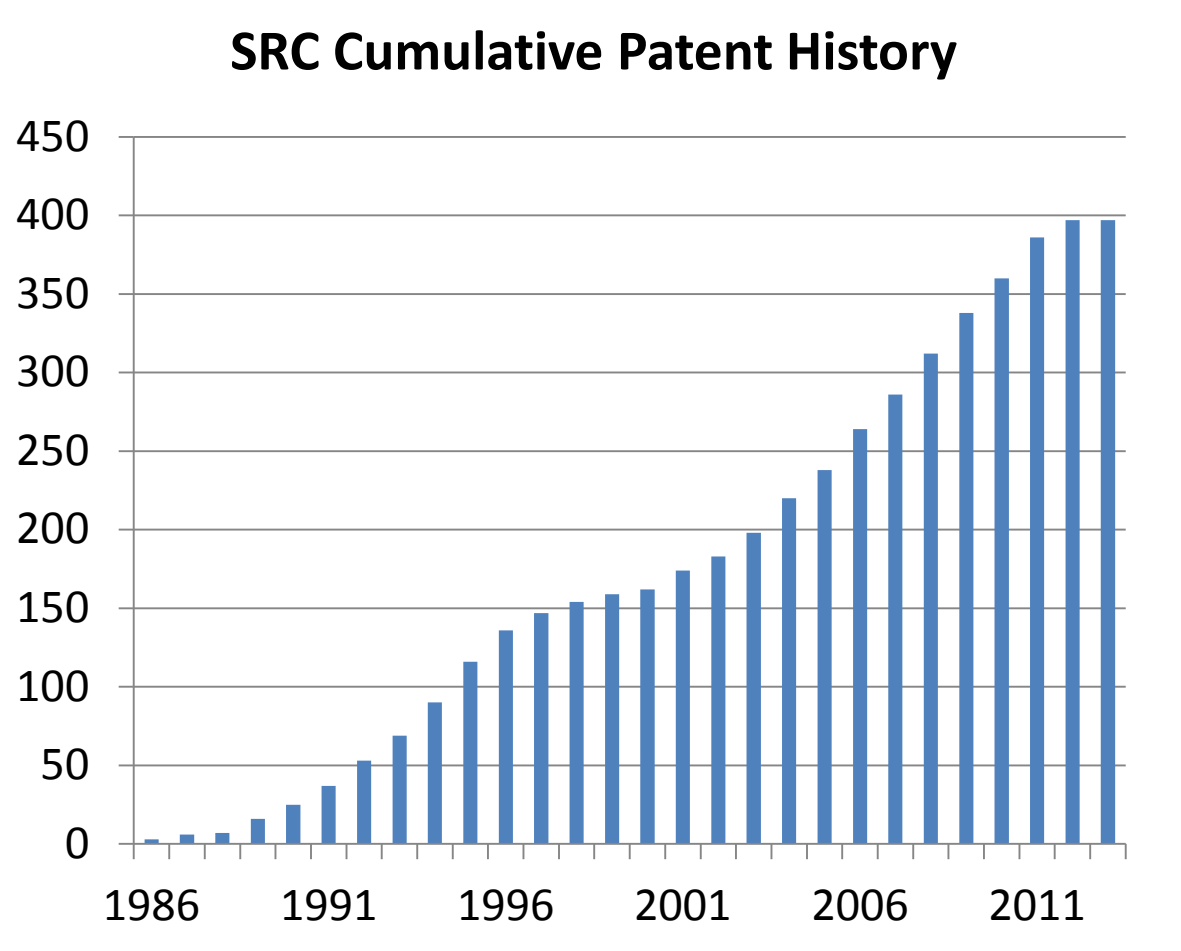
voci™
voci technologies incorporated

Continuous Speech to Text Recognition

Rob A. Rutenbar

Carnegie Mellon University

Intellectual Property Summary



- 289 active patents
- 397 overall
- SRC Average: 14.5

Return to Outline

Technology Futures

The first junction transistor.

- Prognoses from the Current Research Portfolio

Return to Outline

Where Are We Going?

- Some technology projections from current research
  - **Sub-16 nm patterning**
  - **III-V channel FET**
  - **Optical Interconnects**
  - **3D-IC**
  - **Integrated Sensors**
  - **Terahertz Electronics**

III-V channel FET

Research Start: 2003-5

~12 years

Rutgers, UT Dallas, Purdue

Commercialization: (projected) 2015-2018

Need: **Faster Logic**

Solution: **III-V on Si**

Challenge: **Introduction new materials**

Many citations in short time – **Strong interest**

Members citing:

GLOBALFOUNDRIES, intel, IBM, Texas Instruments, freescale

- Original developments in III-V channel FET
- Successful transfer of III-V projects to industry, e.g. through liaisons
- **Influential publications**

Paper Title	Authors	Total Citations	Industry Percentage
"HfO2 and Al2O3 gate dielectrics on GaAs grown by atomic layer deposition", APL 86 (**2005**) 152904	Martin Frank / IBM Eric Garfunkel /Rutgers, et al.	**142**	**21%**
"High-performance inversion-type enhancement-mode InGaAs MOSFET with maximum drain current exceeding 1 A/mm", IEEE ELD 29 (**2008**) 294	Peide Ye / Purdue U et al.	**126**	**18%**
GaAs interfacial self-cleaning by atomic layer deposition, APL 92 (**2008**) 071901	Robert Wallace et al. / UT Dallas	**108**	**24%**

Sub-16 nm patterning

Research Start: 2004

~12 years

U Wisconsin, MIT, UCSB, Stanford

Commercialization: (projected) ~2016

Need:

To sustain Moore's Law in nm-regime

Approach: Directed Self Assembly

Challenge: How to tell matter what to do?

Many citations in short time – **Strong interest**

Members citing:

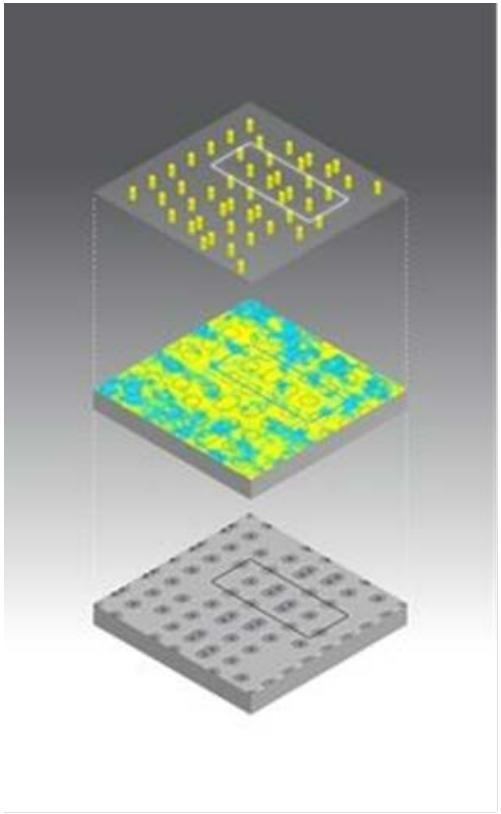
- Original developments in DSA of nanostructures
- Successful transfer of DSA projects to industry, e.g. through liaisons
- **Influential publications**

Paper Title	Authors	Total Citations	Industry Percentage
"Density multiplication and improved lithography by directed block copolymer assembly", Science 321 (**2008**) 936	Paul Nealey et al./ U Wisconsin	**264**	**22%**
"Graphoepitaxy of self-assembled block copolymers on two-dimensional periodic patterned templates", Science 321 (2008) 939	Caroline Rossm, Karl Berggren et al. / MIT	**211**	**16%**

Sub-16 nm patterning

SRC and Stanford Enable Chip Pattern Etching for 14nm

11:00 AM - May 29, 2012 by Douglas Perry - source: SRC
Tom's Hardware.com
http://www.tomshardware.com/news/22nm-14nm-chip-semiconductor-manufacturing,15756.html



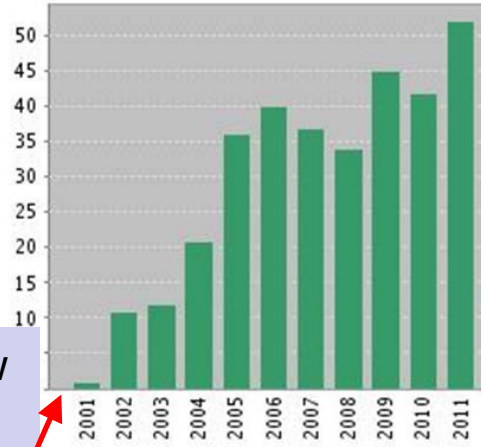
Stanford scientists were able to successfully demonstrate a new directed self-assembly (DSA) process **not just for regular** test patterns, but for **irregular** patterns that are required for the manufacture of smaller semiconductors. This technique will enable pattern etching for next-generation chips down to 14 nm.

3-D Integrated Circuits

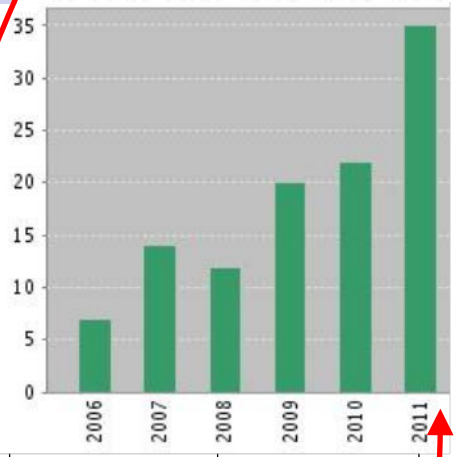
Need:
Fast,
Low-energy,
Multi-functional
Chips

Solution: **Going 3D**

Challenge:
Assembly technology



Citation trajectories show
Growing interest



Members citing:

Mentor Graphics
IBM
intel
GLOBALFOUNDRIES
freescale
cadence
APPLIED MATERIALS
AMD
SYNOPSYS
Predictable Success

Paper Title	Authors	Total Citations	Industry Percentage
3-D Ics: A novel chip design for improving deep-submicrometer interconnect performance and systems-on-chip integration, Proc. IEEE (2001) 602	Krishna Saraswat, et al./ Stanford	343	21%
"Demystifying 3D ICs: The procs and cons of going vertical " IEEE Des. & Test of Comp 22 (2005) 498	Paul Franzon / NCSU	119	19%

Optical Interconnects

Need:
Higher speed Lower energy

Solution:

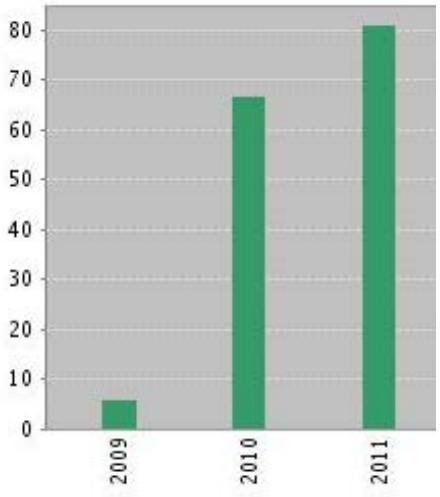
Using light instead of electrons

Challenge:

Optical integration on Si

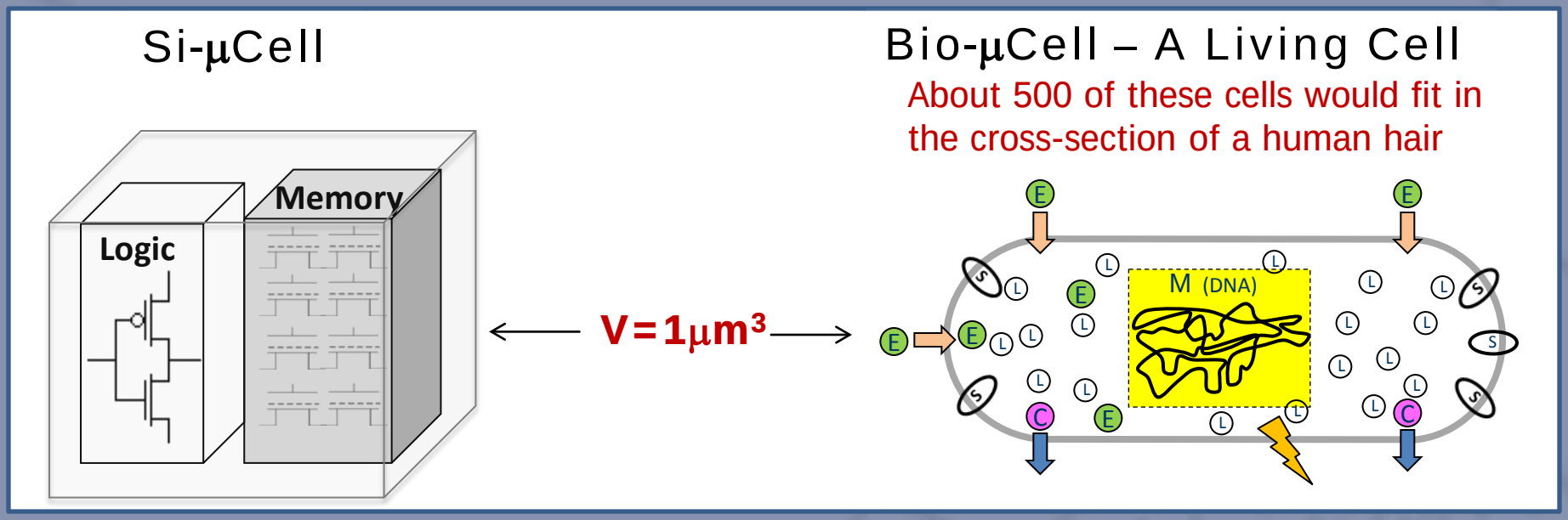
Members citing:

Many citations in short time (continues to grow) – **Strong interest**



Paper Title	Author	Total Citations	Industry Percentage
"Device Requirements for Optical Interconnects to Silicon Chips", Proc. IEEE 97 (2009) 1166	David Miller /Stanford	**195**	**21%**

Nature Has Been Processing Information for a Billion Years



Our studies show that the Si-μCell cannot match the Bio-μCell in the density of memory and logic elements, nor operational speed, nor operational energy:

Memory:	1000x
Logic:	>10x
Power:	1000,000x
Algorithmic efficiency:	1000x

Return to Outline

Many Challenges and Opportunities Stand Before Us

Continue to extend Moore's Law by driving-down integrated circuit fabrication costs

- Even as feature sizes approach atomic dimensions

Expand the space of integrated circuit applications

Dramatically reduce energy consumption of integrated circuits

- May need to invent new devices & interconnect technologies

Expand the sensory domain of integrated circuits

- And learn to utilize the vast amount of data that results

Develop new ways of processing information

- Is it possible to develop machines that reason and discover?

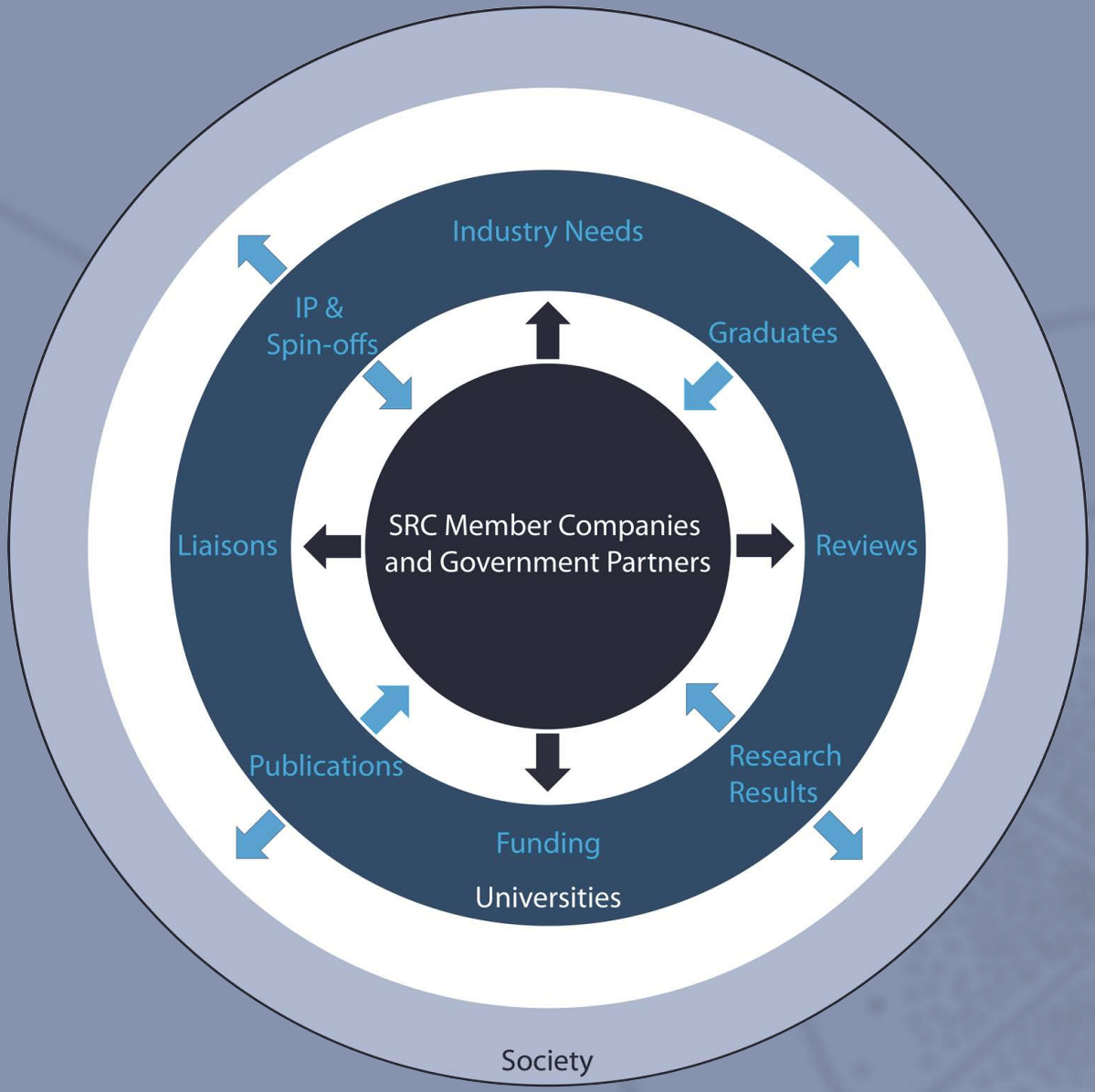
Return to Outline

Working Together We Can Accomplish Wonders!

“Never doubt that a small group of thoughtful, committed people can change the world. Indeed, it is the only thing that ever has.”

– Margaret Mead

Let's Keep Rolling!



Return to Outline

Semiconductor Research Corporation

PIONEERS IN COLLABORATIVE RESEARCH®

Back-Up Charts

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Citations are a Measure of Notable Academic Achievement and Technological Impact

SRC defines papers with at least 100 citations as “influential”

Industry citations are a key!

Citations of Publications on Nobel Prize Winning Research (in the area of semiconductors)

Article	Nobel Prize		# of Citations	
	Awarded	For	25 yrs from publication	2008
Bardeen J, Brattain WH "The Transistor, a Semi-conductor Triode", Phys. Rev. 74 (2): 230-231 1948	1956	Discovery of semiconductor transistor	71	235
Esaki L, "New phenomenon in narrow Germanium p-n junctions", Phys. Rev. 109 (1958) 603	1973	Discovery of tunnel diode	247	547
Kroemer H, "Heterostructure Bipolar-transistors and Integrated-circuits", PROC. of the IEEE 70 (1982) 13	2000	Invention of heterojunctions	577	609

Note that several papers underlying these Nobel Prize winning technologies received several hundred citations.

Percent of Influential Publications at Top Universities

- Below is an analysis of publications from a sampling of Top-100 ranked universities across the world (according to ARWU).
- Includes all publications between 1899 and 2010.

University	Total # of Publications	# of Influential Publications	Percent
UC Berkeley	226,739	11,623	5.13
U Oxford	260,171	9,958	3.83
Leiden U	66,732	2,172	3.25
U Copenhagen	71,367	1,974	2.77
Purdue U	113,689	2,774	2.44
U Oslo	55,016	1,227	2.23
U Sydney	95,534	1,848	1.93
U Bonn	61,651	1,158	1.88
Kyoto U	6,722	98	1.46
Moscow State U	122,561	503	0.41
	922,997	**33,335**	**3.61**

Only ~3.6% of papers receive more than 100 citations.

* Academic Ranking of World Universities (ARWU) ranking based on number of alumni and staff awarded Nobel Prize or Fields Medal, number of highly cited researchers according to Thomson Scientific, number of articles published in *Nature* or *Science*, number of articles indexed in Science Citation Index-Expanded and Social Sciences Citation Index, and per capita performance with respect to the size of an institution.

IEEE Journals: Citation Statistics

	Totals (through 2010)			Average per year				
IEEE Journal	**Pubs**	**Citations**	**100+**	**Pubs**	**Citations**	**100+**	**% of 100+**	**Avg. cit/pub**
IEEE Transactions on Electron Devices	16,807	245,899	304	357.60	5,231.89	6.47	1.8%	14.63
Proceedings of the IEEE	19,949	279,959	548	231.97	3,255.34	6.37	2.7%	14.03
IEEE Electron Device Letters	6,433	103,644	111	207.52	3,343.35	3.58	1.7%	16.11
IEEE Journal of Solid State Circuits	8,813	158,184	218	195.84	3,515.20	4.84	2.5%	17.95
IEEE Circuits and Devices Magazine	615	1,522	2	61.50	152.20	0.20	0.3%	2.47
IEEE Trans. on CAD of Integrated Circuits and Systems	3,952	51,897	52	146.37	1,922.11	1.93	1.3%	13.13
IEEE Transactions on Computers	7,324	124,501	184	166.45	2,829.57	4.18	2.5%	17.00
IEEE Transactions on Nanotechnology	820	9,076	8	91.11	1,008.44	0.89	1.0%	11.07
IEEE Transactions on Reliability	4,165	31,444	20	88.62	669.02	0.43	0.5%	7.55
Averages	**7,653**	**111,792**	**161**	**171.89**	**2,436.35**	**3.21**	**1.60%**	**12.66**

In these IEEE publications, **1.60%** of articles receive 100+ citations, and the average number of citations is **12.66**.

Technology Transfer Indicators

Est. Research Start	Research/Influential Article	Researchers	# of citations		Commercial Application		
			Total	By Industry	Technology	Year	Company Products
1984	"BSIM - Berkeley Short-Channel IGFET Model for MOS-Transistors", *IEEE J. S-State Cir* 22 (1987) 558	Sheu et al **UC/Berkeley**	200	55 (28%)	Compact Modeling Tools; Formal Verification Tools; Logic Synthesis Tools; Simulation Tools	1992	Synopsis; Cadence
1983	"Graph-based algorithms for Boolean function manipulation", *IEEE Trans on Comput* 35 (1986) 677	Bryant **CMU**	1754	321 (18%)			
1987	"Asymptotic wave-form evaluation for timing analysis", *IEEE Trans Computer-Aided Design* 9 (1990) 352	Pillage and Rohrer **UT/Austin & CMU**	762	206 (27%)			
1990	"Threshold voltage model for deep-submicrometer MOSFET's", *IEEE Trans Electron Dev* 40 (1993) 86	Liu, Hu et al. **UC/Berkeley**	209	73 (35%)			
1994	"Multilevel interconnections for ULSI and GSI era", *Mat Sci & Engn R-Reports* 19 (1997) 87	Murarka, **RPI**	258	54 (21%)	Cu, low-K, &multilevel interconnects	2000	IBM; TI; Freescale; Connexant; LSI; Flip-Chip Tech
1998	"The future of wires", *Proc IEEE* 89 (2001) 490	Ho, Mai et al. **Stanford U**	429	89 (21%)			
2000	"Recent advances on electromigration in very-large-scale-integration of interconnects", *JAP* 94 (2003) 5451	Tu, **UCLA**	369	99 (27%)			
1986	"Point-Defects and Dopant Diffusion in Silicon", *Rev Mod Phys* 61 (1989) 289	Fahey, Plummer **Stanford U**	847	261 (31%)	Sub-100 nm MPU and Flash	2001	Intel; AMD; GF; Freescale; TI; NORTEL; IBM; Digital Equip. Corp
1994	"Making silicon nitride film a viable gate dielectric", *IEEE Trans on Electron Dev* 45 (1998) 680	Ma, **Yale U**	220	56 (25%)			
2000	"Tin-lead (SnPb) solder reaction in flip chip technology", *Mat Sci &Engn R-Reports* 34 (2001) 1	Tu, Zeng, **UCLA**	293	45 (15%)	Flip chip 'Green' (lead-free) IC products	2005	IBM; Connexant; TI; Flip Chip Tech; Intel; Freescale
2000	"Six cases of reliability study of Pb-free solder joints in electronic packaging technology", *Mat Sci & Engn R-Reports* 38 (2002) 55	Zeng, Tu **UCLA**	578	99 (17%)			

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Current & Projected Technology Transfers

Res. Start	Research/Influential Article	Researchers	# of citations		Commercial application		
			Total	By Industry	Technology	Year	Company
1999	"High-k gate dielectrics: Current status and materials properties considerations", *JAP* 89 (2001) 5243	Wilk GD (Agere) Wallace R, Anthony J **U North Texas & South Florida**	3077	831 (27%)	45 nm MPU	2008	Intel; TI
1998	"Alternative dielectrics to silicon dioxide for memory and logic devices", *Nature* 406 (2000) 1032	Kingon AI et al. **NC State Univ**	631	149 (24%)			
1994	"Elementary scattering theory of the Si MOSFET", *IEEE Electron Dev Lett* 18 (1997) 361	Lundstrom **Purdue U**	283	63 (22%)	Device Modeling Tools	2008+	Intel; IBM; Freescale; LSI; TI; AMD
1999	"Essential physics of carrier transport in nanoscale MOSFETs", *IEEE Trans on Electron Dev* 49 (2002) 133	Lundstrom , Ren **Purdue U**	228	59 (26%)			
1998	"Leakage current mechanisms and leakage reduction techniques in deep-submicrometer CMOS circuits", *Proc IEEE* 91 (2003) 305	Roy K et al. **Purdue U**	345	85 (25%)	Low-power IC products	2010+	Intel; AMD; IBM; HP
1993	"The impact of intrinsic device fluctuations on CMOS SRAM cell stability", *IEEE J. S-State Cir* 36 (2001) 658	Bhavnagarwala , Tang et al. **Georgia Tech**	217	94 (43%)			
1996	"Step and flash imprint lithography: A new approach to high-resolution patterning", *Emerging Lithographic Tech III Pts 1 and 2* 3676 (1999) 379	Colburn, Willson et al. **U Texas/Austin**	350	148 (42%)	22 nm patterning	2012+	*Anticipated:* ***TI; IBM; Intel; GF; LSI***
1996	"Step and flash imprint lithography: Template surface treatment and defect analysis", *JVST B* 18 (2000) 3572	Bailey, Willson et al. **U Texas/Austin**	238	88 (37%)			
2005	"Directed assembly of block copolymer blends into nonregular device-oriented structures", *Sci* 308 (2005) 1442	de Pablo, Nealey et al. **U Wisconsin**	286	48 (17%)	Sub-22 nm patterning	***2014*** *Projected*	*Anticipated:* ***IBM; Intel; AMAT; GF; Micron***
1998	"3-D ICs: A novel chip design for improving deep-submicrometer interconnect performance and systems-on-chip integration", *Proc of IEEE* 89 (2001) 602	Banerjee, Souri, Kapur **Stanford U**	279	63 (23%)	3-D ICs	***2015*** *Projected*	*Anticipated:* ***Intel; TI; Freescale; IBM***