“We look before and after …”

Thomas Kailath
Stanford University

Paths Ahead Symposium

Nov 12 – 14, 2009

Laboratory for Information and Decision Systems (LIDS)

Massachusetts Institute of Technology

… and pine for what is not.”

(P.B. Shelley)

Introduction

Some of my most enjoyable research has involved the cross fertilization of ideas from rather different fields.

Sanjoy is quite familiar with such pleasures. In his honor I had thought I would choose an example of results that were first presented in 1972, which was when we really began our long, happy and fruitful association and interactions.

The event was a seminar at Imperial College. Ironically a few months ago in London, I completed that story by describing an application that no one had imagined in 1972.

From Radiative Transfer Theory To Fast Algorithms for Cell Phones

Thomas Kailath
Stanford University

We describe how analogies between certain problems in statistical prediction and in radiative transfer led, *inter alia*, to the development of new fast algorithms (and efficient integrated circuit implementations thereof) for a host of problems in the fields of communications, control, signal processing, linear algebra and operator theory.

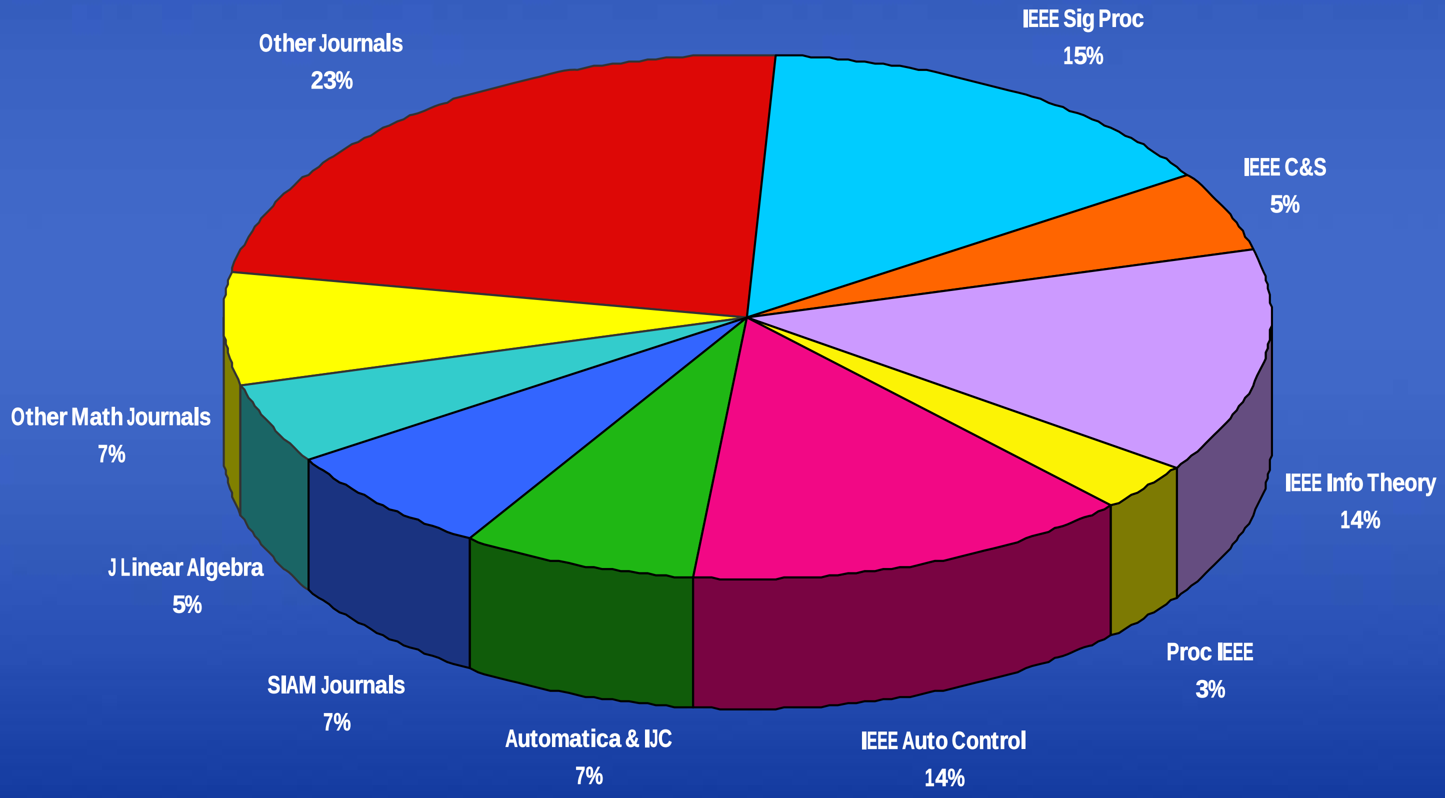
New Fellows Seminar
The Royal Society
London
9th July 2009

While repeating that presentation would have been the Path of Least Resistance, it would have disappointed our chairs, Alan Willsky and Tom Magnanti, who have put so much effort into organizing this remarkable symposium.

So at the risk of not really telling you anything surprising, I am going to describe *how the evolution of my career over the last 50 years has led me to the following (not original) conclusion :*

While there will always be a need for deep and innovative theoretical research, we could be devoting more effort now to developing multidisciplinary teams to define and tackle problems in the many nationally challenging areas where the "systems approach" and the results of over 50 years of work in control, communications, computation, optimization, simulation and signal processing can be fruitfully employed.

Pie chart of Publications ca 1995



A Bird's Eye View

1960s: Multipath Channels, Signal Detection, Feedback Communications

1970s: Estimation Theory, Stochastic Processes, Linear Systems

1980s: VLSI Systems, Sensor Array Processing, Displacement Structure

1990s: Adaptive Filtering, Semiconductor Manufacturing, Wireless Communications

Each decade came not only with a change in research fields, but also a change in the mode of research

The Path to Semiconductor Manufacturing

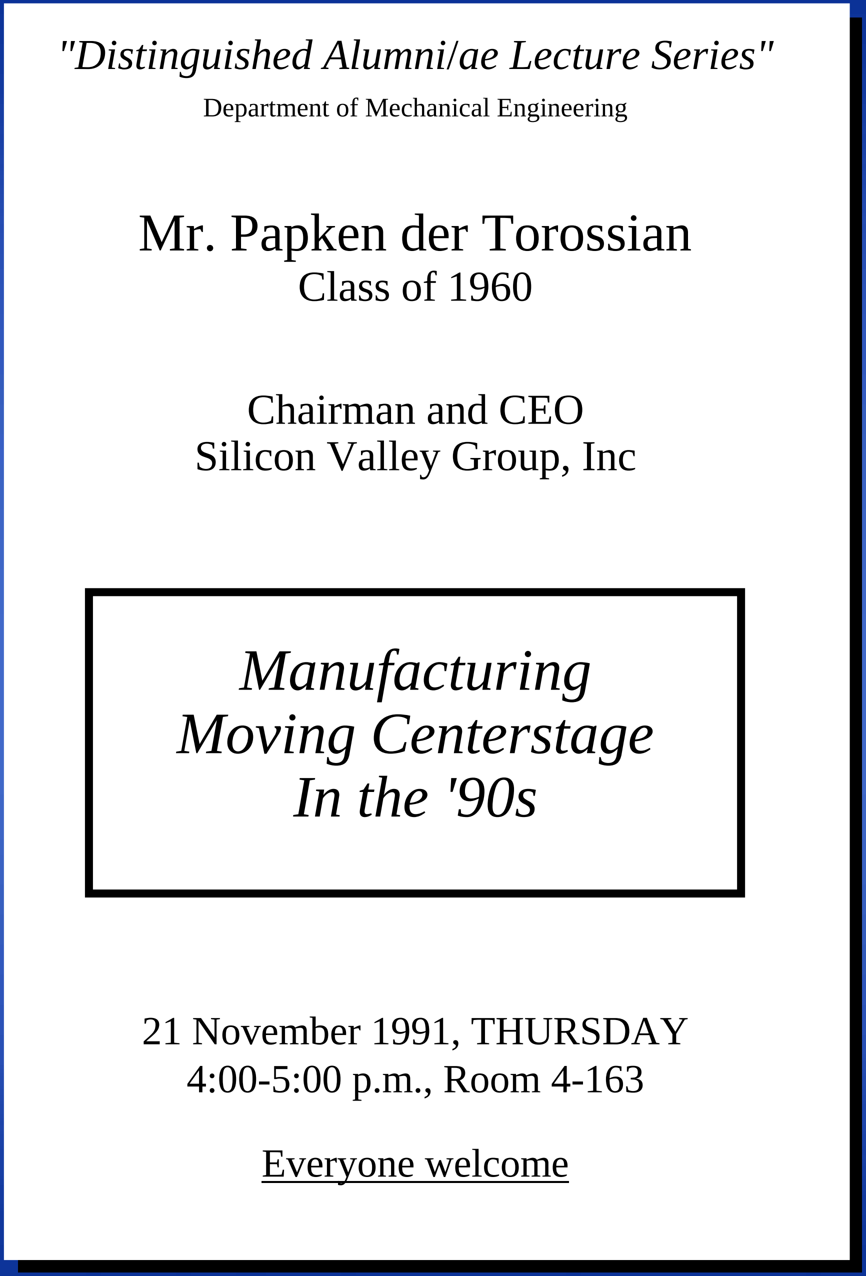
In the 60s, following the then MIT pattern, my research and publications (with two exceptions) were quite distinct from those of my first dozen Ph.D. students.

In the 70s, I needed more understanding of control theory and multivariable linear systems and I began to rely on my students to teach me about them. Then the realization that university research should be about " intelligence amplification" led me to begin to work along with them.

The putting together of teams to enter quite unfamiliar research areas began in the 80s with our venture into VLSI systems. Its success then made that the model for most of my subsequent research projects.

Here I shall only describe our work in the 90s on semiconductor manufacturing, a response to a challenge from Prof. Louis Auslander, at the time Director of DARPA's Math program. He had originally wanted to support my work in Algebra and Operator Theory .

A long way from manufacturing! And thereby hangs a tale.



"Distinguished Alumni/ae Lecture Series"

Department of Mechanical Engineering

Mr. Papken der Torossian

Class of 1960

Chairman and CEO
Silicon Valley Group, Inc

Manufacturing Moving Centerstage In the '90s

21 November 1991, THURSDAY
4:00-5:00 p.m., Room 4-163

Everyone welcome

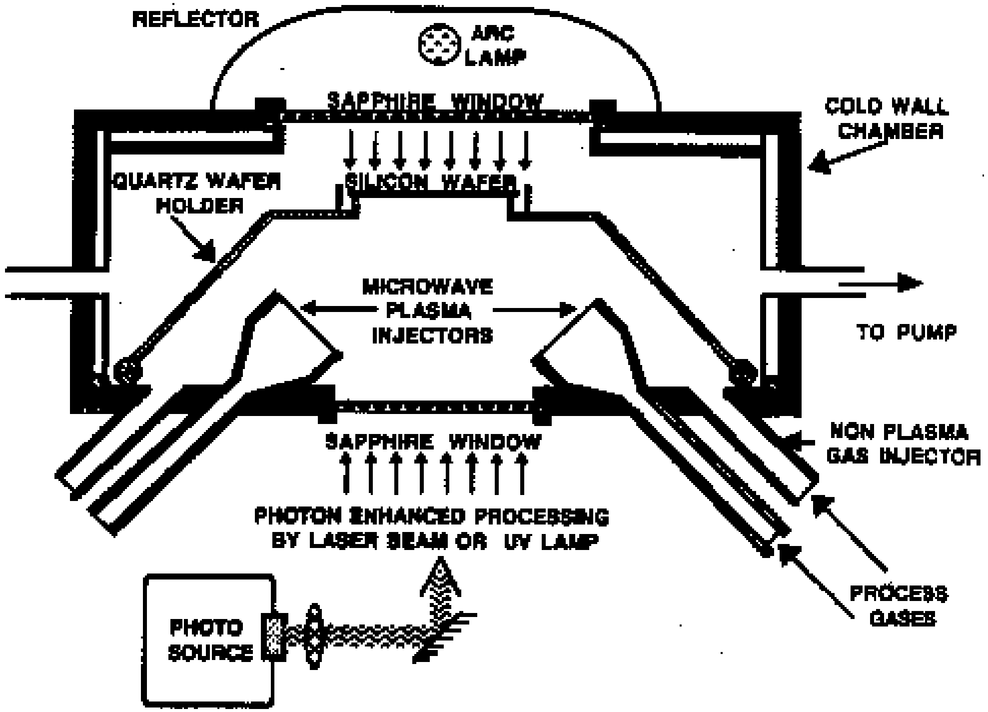
Microelectronics Manufacturing Science and Technology (MMST) Project

$150M over 4 years from the Air Force to Texas Instruments to validate the feasibilty of a new paradigm for semiconductor manufacturing

Final Demonstration (May, 1993): 1,000 wafer marathon run of two 0.35 µm CMOS process technologies in a 100% single wafer processing factory .

TODAY'S STATE-OF-THE-ART FAB	GOAL: FLEXIBLE INTELLIGENT FAB
Large volumes of a single part type	Many part types, many processes in any volume
25,000 wafers/month of DRAMs minimum	Minimum of 1,000 wafers/month of high-value-added, differentiated products (logic, ASICs)
$500M entry cost ($1.58B by 2000)	~ $50M entry cost
3-year life for fixed capacity	Clusters and CIM form factory "backbone" for inexpensive, rapid upgrades and capacity growth

RAPID THERMAL MULTIPROCESSING REACTOR

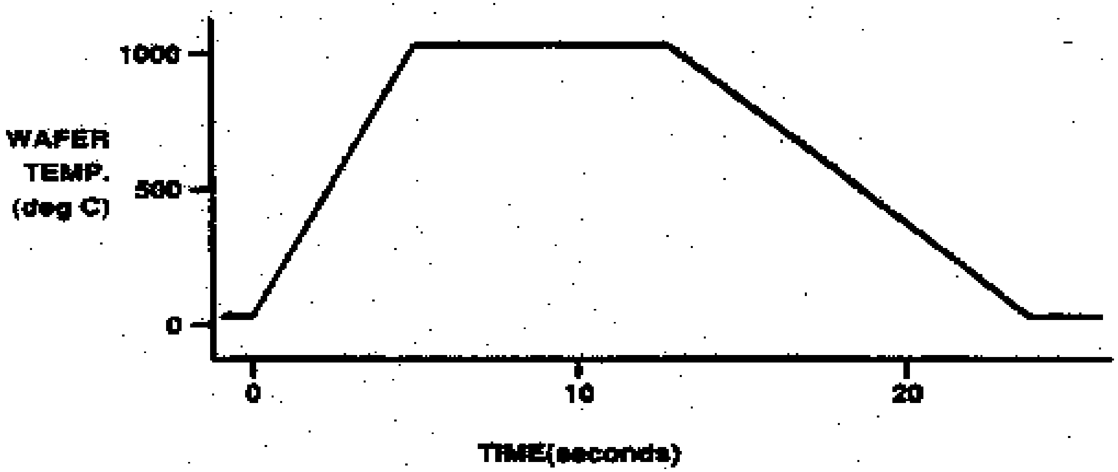


- * LAMPS FOR RAPID THERMAL PROCESSING
- * REMOTE MICROWAVE PLASMA PROCESSING
- * UV PHOTO PROCESSING

IN-SITU CLEANING, GROWTH AND DEPOSITION OF SEMICONDUCTORS, DIELECTRICS AND METALS

The RTP Temperature Control Problem

A typical RTP temperature trajectory:



Requirements:

- Fast ramp-up and cool-down
  - high throughput
  - minimal dopant diffusion
- precise trajectory following for process repeatability
- near-uniform temperature across wafer at all times
  - uniform processing
  - no damage from thermal stress

The Stage

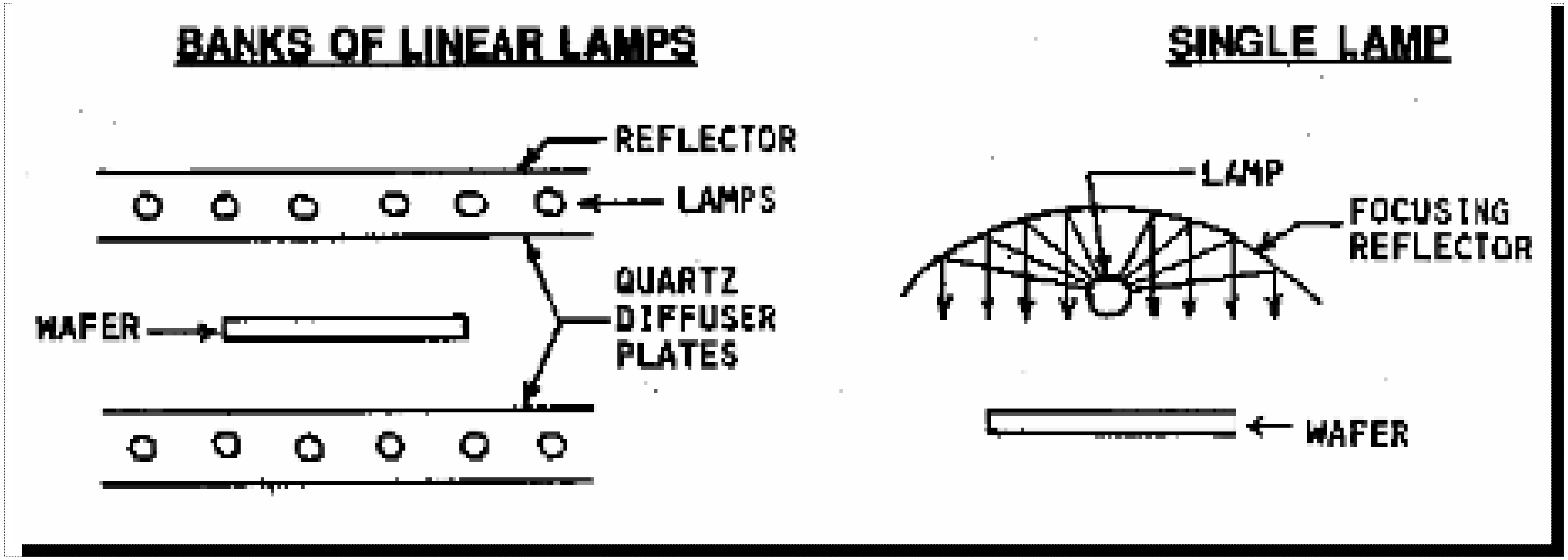
It was at this time that we received the DARPA challenge and were lucky to find that Prof Saraswat from Stanford's Center for Integrated Systems had been working for a year on the MMST project as a subcontractor to Texas Instruments.

This set the stage for Profs. Boyd, Franklin and me from the Information Systems Lab , and of course a group of fresh ISL students, to join Prof Sarawat on this project. We were lucky to find a post-doc, Charles Schaper from UCSB, who had a chemical engineering and controls background and so had some familiarity with the new jargon: CVD poly, wet RTO, etc., etc.

Several small companies produced systems, each using different heat-lamp configurations and (single variable) control algorithms to try to achieve what the conventional wisdom decreed---uniform heat flux over the wafer, over the whole cycle.

The approach was largely empirical, based on trial and error to tweak the control parameters. It was not untypical of the industry at the time.

Commonly Used Lamps for RTP



The Systems Approach

This first step is to abstract and simplify a real-world problem so that one can make a mathematical model for the problem: in automatic tracking and control, VLSI design, feature detection in images, high-speed digital communications in various environments, diverse problems in semiconductor manufacturing, and many others.

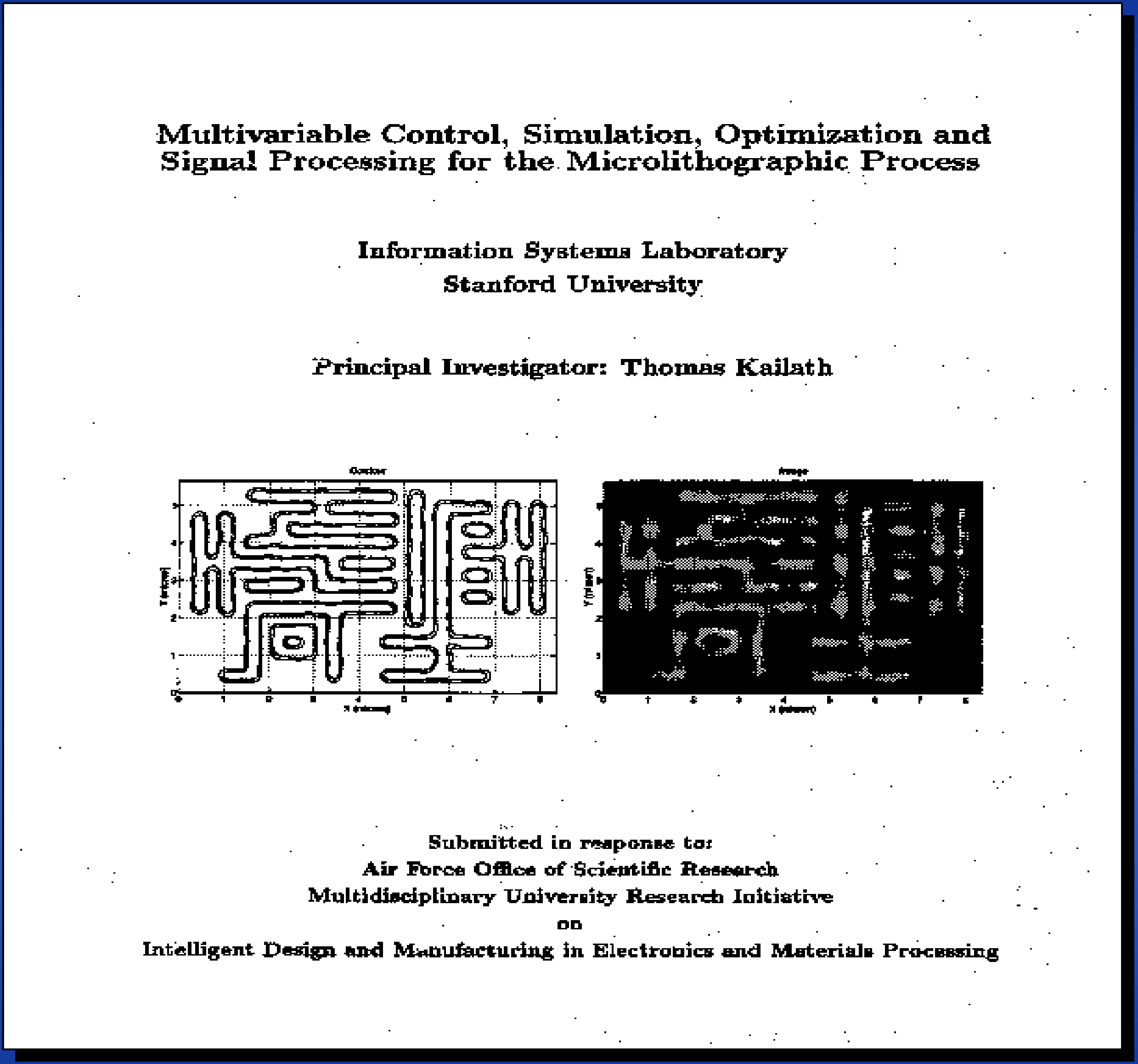
Secondly, one uses, and sometimes develops *ab initio*, a variety of often surprisingly advanced mathematical tools to solve the idealized problem.

The final step is to gain a sufficiently physical and intuitive understanding of the mathematical solution that one can translate it into a "practical" solution of the original physical problem. The word "practical" of course has many aspects, from technical feasibility to economic viability

Needless to say, the systems approach worked (again), with Chuck Schaper playing a key role shuttling back and forth between Dallas and Stanford. The first step was to conclude from the analysis of simple models that the conventional wisdom was wrong. We need non-uniform *heat flux over the wafer. Moreover* multivariable *control is essential*.

CHRONOLOGY OF TECHNOLOGY TRANSFER FROM STANFORD TO TEXAS INSTRUMENTS

(1/90 – 8/90)	Modeling of heat transfer for RTP Optimization and simulation of performance limits Comparison of multizone lamp configurations
(9/90 – 5/91)	Development and simulation of controllers
(6/91 – 3/92)	Experimental demonstration on Stanford RTM
(4/92 – 12/92)	Transfer and customization on 8 RTPs, 13 different processes at TI
(1/93 – 5/93)	Usage for 1,000 wafer MMST marathon demo



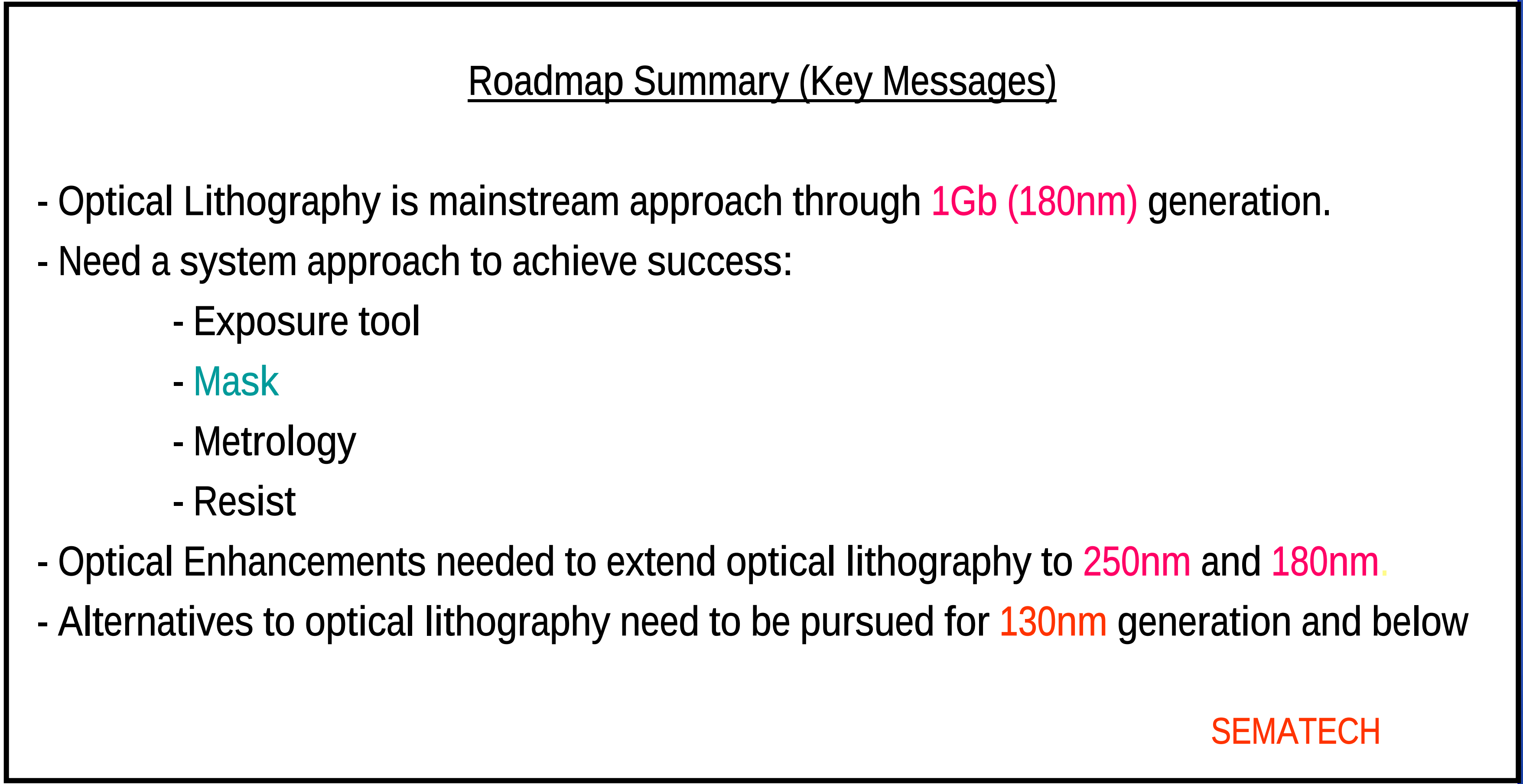
Multivariable Control, Simulation, Optimization and Signal Processing for the Microlithographic Process

Information Systems Laboratory
Stanford University

Principal Investigator: Thomas Kailath

Submitted in response to:
Air Force Office of Scientific Research
Multidisciplinary University Research Initiative
on
Intelligent Design and Manufacturing in Electronics and Materials Processing

The Lithography Challenge in 1994



Roadmap Summary (Key Messages)

- Optical Lithography is mainstream approach through 1Gb (180nm) generation.
- Need a system approach to achieve success:
  - Exposure tool
  - Mask
  - Metrology
  - Resist
- Optical Enhancements needed to extend optical lithography to 250nm and 180nm.
- Alternatives to optical lithography need to be pursued for 130nm generation and below

SEMATECH

K. Brown/DSRC 7/6/94

Figure 3: Slide presented by Dr. K. Brown of SEMATECH at the DSRC Meeting in San Diego (copied with permission).

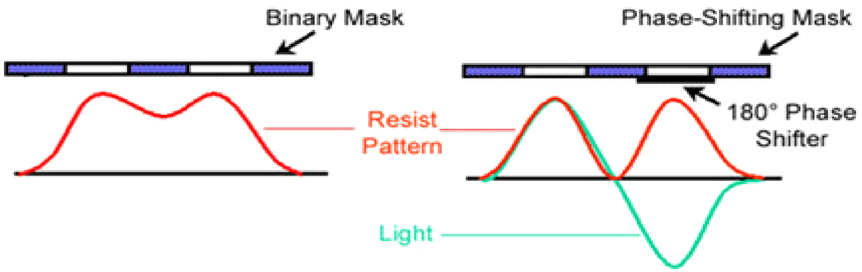
Breaking the 0.1 Barrier in Optical Microlithography via Signal Processing:
From Doctoral Research to Wall Street

Distinguished Lecture
Department of Electrical Engineering
Princeton University

Thomas Kailath

Hitachi America Professor of Engineering, Emeritus
Stanford University

The progression of processing power, as predicted by Moore’s Law, depends on ever-narrowing the line-widths in semiconductor lithography. The current predicted resolution limit for optical lithography is around 0.1 µm, using 193 nm laser sources and resists that are still under development. Beyond that, there first seemed to be three options: X-rays, e-beam, and EUV (with mirrors instead of lenses). At present, only the last one has survived, though it is not projected to be production-worthy for another 8-10 years! Fortunately, it appears that signal processing ideas can allow us to go well beyond the so-called "0.1 barrier" with existing optical technology. This talk will describe how these ideas emerged from Stanford Ph.D. dissertations, were developed into realistic practical implementation, and ultimately led to the creation and success of the now-public company Numerical Technologies. This talk is directed to a general audience as an illustration of the familiar engineering path, from an ill-defined physical problem to an idealized mathematical model, its approximate solution, implementation and transition to industry.



Preaching to the Choir

(Extracts from Prof. Grimson's Course VI Report, Fall 2008)

"We continue to pursue the influence of electrical engineering and computer science research methodologies in health sciences, finance, energy, environment, and other areas, building on our tagline that "EECS is everywhere"; and we continue our active outreach efforts, encouraging potential students to consider the wealth of exciting opportunities open to someone skilled in the analytical methods of electrical engineering and computer science.

We are particularly intrigued with how much the research interests of our faculty and students are focused on problems motivated by compelling human needs: energy, environment, transportation, health; and they reflect the commitment of our faculty and students to making an impact on the world. "

"There is Nothing so Practical as a Good Theory"-Boltzmann

(From a 2007 New York Times column by Thomas Friedman)

"The first student exhibit I visited was by Yuval Sharoni, 26, an electrical engineering senior whose project was titled

Innovative Covariance Matrix for Point Target Detection in Hyperspectral Images

When I told him I was from the New York Times, he declared:

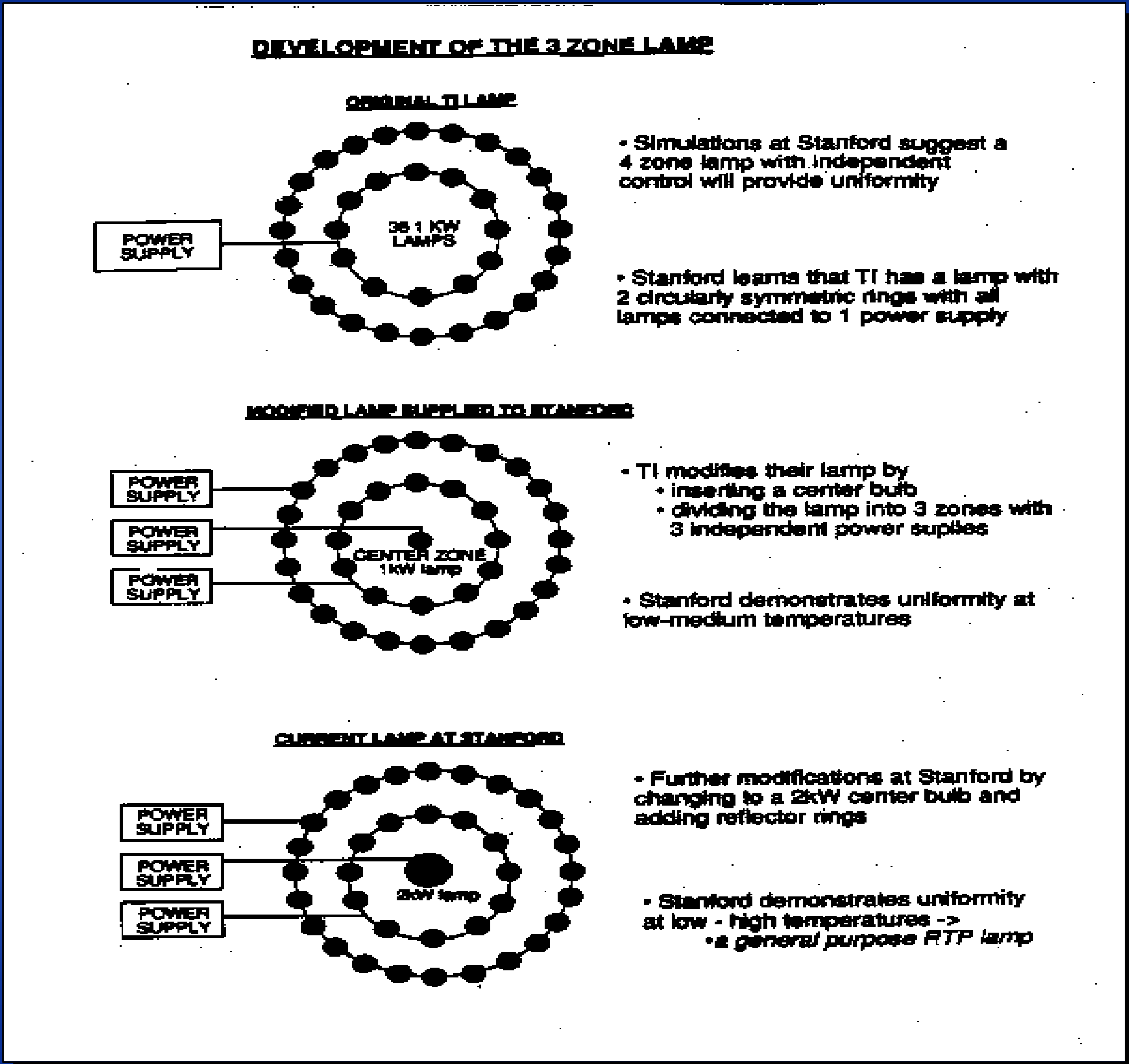
'This project is going to make the front page, I am telling you.'

The cover of Popular Mechanics, maybe, but it could one day make the NASDAQ, …"

Ave Sanjoy !

And of course this brings us back to the abiding importance of theory, which Professor Sanjoy Mitter has eloquently and stalwartly emphasized, encouraged and defended, through his innovative and fundamental contributions and his distinguished leadership of LIDS and the Center for Intelligent Control.

Thank You



DEVELOPMENT OF THE 3 ZONE LAMP

ORIGINAL TI LAMP

- Simulations at Stanford suggest a 4 zone lamp with independent control will provide uniformity
- Stanford learns that TI has a lamp with 2 circularly symmetric rings with all lamps connected to 1 power supply

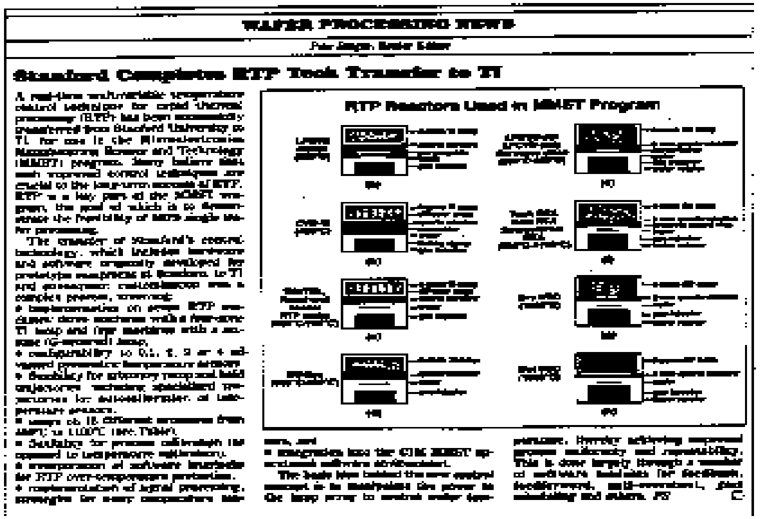
MODIFIED LAMP SUPPLIED TO STANFORD

- TI modifies their lamp by
  - inserting a center bulb
  - dividing the lamp into 3 zones with 3 independent power suplies
- Stanford demonstrates uniformity at low-medium temperatures

CURRENT LAMP AT STANFORD

- Further modifications at Stanford by changing to a 2kW center bulb and adding reflector rings
- Stanford demonstrates uniformity at low - high temperatures ->
  - *a general purpose RTP lamp*

Semiconductor International, Vol. 16, No. 7, pg. 56, June 1993.



WAFER PROCESSING NEWS

Stanford Completes RTP Tech Transfer to TI

RTP Reactors Used in MMST Program

8 reactors

13 processes

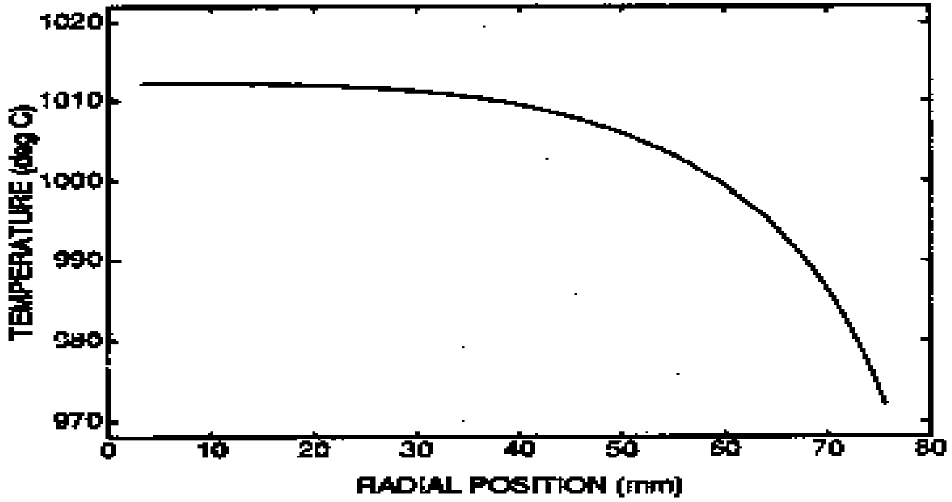
- CVD Nitride
- CVD Poly
- CVD Tungsten
- CVD aSi
- TiN/TiSix React
- TiN/TiSix Anneal
- Wet RTO
- Dry RTO
- Germane Clean
- RTP Sinter
- Tank RTA
- Gate RTA
- S/D RTA

- Developed and transferred control technology to TI for their ARPA/AF MMST program and successful final demonstration in May, 1993.
- Our controller was licensed via MMST to CVC, Inc.; being implemented on their current (1995) 200 mm RTP equipment and being scaled for their next generation (300 mm) product line.
- The same control methodology is currently being applied to design an advanced "bake/chill" unit for deep UV microlithography (useful interactions with SVG and SEMATECH).

Uniform Illumination for Uniform Temperature?

Early RTP lamp designs attempted to ensure uniform Illumination of the top surface of the wafer.

A typical resulting steady-state temperature profile:



Temperature is nonuniform because:

- radiative and convective losses at the edge set up a temperature gradient;
- convective loss coefficients tend to be higher nearer the wafer edge.

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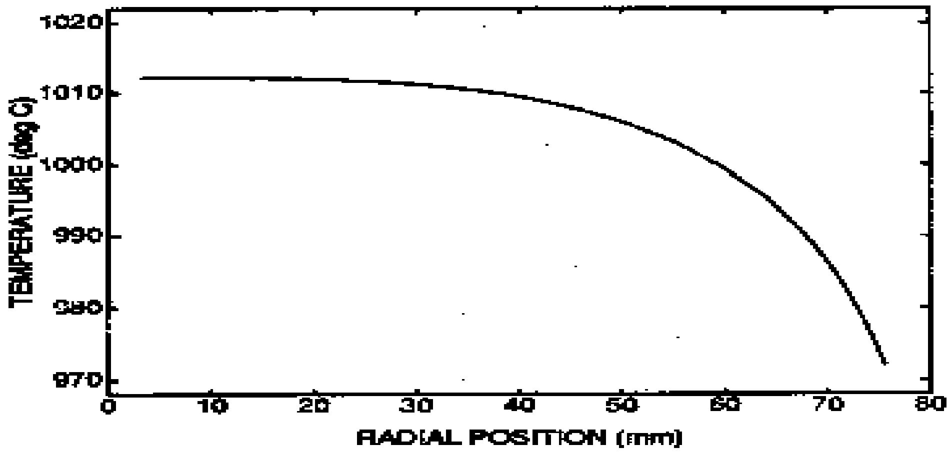

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