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Nanofabrication

**DISCOVERY LECTURE SERIES**
2006 PURDUE UNIVERSITY



Nanofabrication

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Papers and Discussions Presented
at the Joint Computer Conference
Philadelphia, Pa., December 3-5, 1958

An Approach to Microminiature Printed Systems

D. A. BUCK

K. R. SHOULDERS

THE DAY is rapidly drawing near when digital computers will no longer be made by assembling thousands of individually manufactured parts into plug-in assemblies and then completing their interconnection with back-panel wiring. An alternative to this method is one in which an entire computer or a large part of a computer is made in a single process. Vacuum deposition of electrodes onto blocks of pure silicon or germanium and the subsequent diffusion of the electrode material into the block to form junctions is a most promising method. The successful development of this method would allow large numbers of transistors and all

of their interconnecting wiring to be made in one operation. Vacuum deposition of magnetic materials and conductors to form coincident-current magnetic-core memory planes is a second promising method that will allow an entire memory to be made in one operation. The vacuum deposition of superconductive switching and memory circuits is a third method that will make possible the printing of an entire computer. The authors feel sure that the most significant milestone in computer component technology will be the announcement by one or more firms, in perhaps 2 years, that all of the technical problems of building a printed system

have been solved, and that one of their engineers with his vacuum system can make a digital computer in an hour.

All three methods mentioned, as well as others not mentioned, involve vacuum deposition through a mask. A cleaned glass substrate or a semiconducting surface is placed in a vacuum system, and the air pumped out until the residual pressure is below 10^{-4} atmosphere. A piece of metal near to the substrate is then heated and atoms of that metal evaporate. Some condense onto the substrate, forming a thin film. Between the source of atoms and the substrate a mask is placed to in-

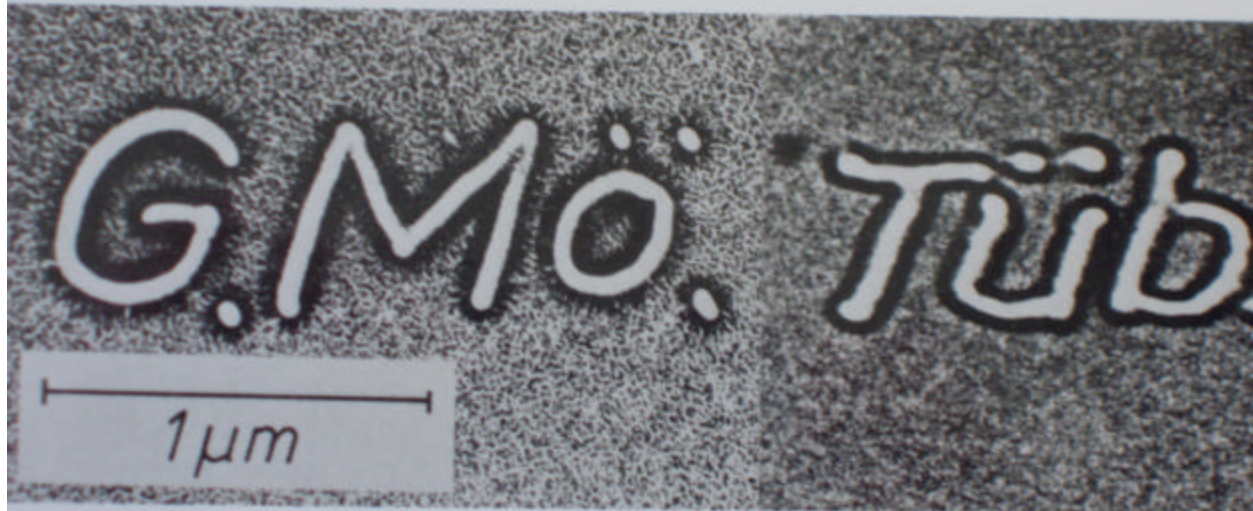
D. A. BUCK (deceased) was with Massachusetts Institute of Technology, Cambridge, Mass.

K. R. SHOULDERS is with Stanford Research Institute, Menlo Park, Calif.

This paper is part of a panel discussion on "The Impending Revolution in Computer Technology."

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Mollenstedt and Speidel, 1960
one of the first examples of
'Nanowriting' using a modified
transmission electron microscope to
reform a collodion film and then
shadowing with evaporated metal
G. Mollenstedt and R. Speidel,
Physikalische Blatter, February
1960).



Heise, 1963 SEM 5 (Tx-mode),
'Free-standing contamination
Structures'



750Å



750Å

IT WAS THE BEST OF TIMES, it was the worst of times, it was the age of
 wisdom, it was the age of foolishness, it was the epoch of belief, it
 was the epoch of incredulity, it was the season of light, it was the
 season of darkness, it was the spring of hope, it was the winter of
 despair, we had everything before us, we had nothing before us, we were
 all going direct to Heaven, we were all going direct the other way-in
 short, the period was so far like the present period, that some of its
 noisiest authorities insisted on its being received, for good or for
 evil, in the superlative degree of comparison only. There were a king
 with a large jaw and a queen with a plain face, on the throne of Eng-
 land; there were a king with a large jaw and a queen with a fair face
 on the throne of France. In both countries it was clearer than crystal
 to the lords of the State preserves of loaves and fishes, that things
 in general were settled for ever. It was the year of Our Lord one thou-
 sand seven hundred and seventy-five. Spiritual revelations were con-
 ceded to England at that favoured period, as at this. Mrs Southcott had
 recently attained her five-and-twentieth blessed birthday, of whom a
 prophetic private in the Life Guards had heralded the sublime appear-
 ance by announcing that arrangements were made for the swallowing up of
 London and Westminster. Even the Cock-lane ghost had been laid only a
 round dozen of years, after rapping out its messages, as the spirits of
 this very year last past (supernaturally deficient in originality)
 rapped out theirs. Here messages in the earthly order of events had
 lately come to the English Crown and People, from a congress of British
 subjects in America; which, strange to relate, have proved more impor-
 tant to the human race than any of the chickens of the Cock-lane brood.

France, less favoured on the whole as to matters spiritual than her
 sister of the shield and trident, rolled with exceeding smoothness down
 hill, making paper money and spending it. Under the guidance of her
 Christian pastors, she entertained herself, besides, with such humane
 achievements as sentencing a youth to have his hands cut off, his
 tongue torn out with pincers, and his body burned alive, because he had
 not kneeled down in the rain to do honour to a dirty procession of
 monks which passed within his view, at a distance of some fifty or six-
 ty yards. It is likely enough that, rooted in the woods of France and
 Norway, there were growing trees, when the sufferer was put to death,
 already marked by the woodman, fate, to come down and be sawn into
 boards, to make a certain naveble framework with a sack and a knife in
 it, terrible in history. It is likely enough that in the rough out-
 houses of some tillers of the very lands adjacent to Paris, there were
 sheltered from the weather that very day, rude carts, bespattered with
 rustic mire, snuffed about by pigs, and roosted in by poultry, which
 were to be the theatre of the French Revolution. But that woodman and that feller, though they work unceasing-
 ly, work silently, and no one heard them as they went about with suf-
 ficed trees: the rather, forasmuch as to entertain any suspicion that
 they were awake, was to be atheistical and traitorous. In England,
 there was scarcely an amount of order and protection to justify such
 national boasting. Boring burglaries by armed men, and highway robber-
 ies, took place in the capital itself every night; families were...

5.9mm



CALIFORNIA INSTITUTE OF TECHNOLOGY

CHARLES C. LAURITSEN LABORATORY OF HIGH ENERGY PHYSICS

November 19, 1985

Dr. Thomas H. Newman
452 McCullough Building
Stanford University
Stanford, CA 94305

Dear Dr. Newman:

Congratulations to you and your colleagues. You have certainly satisfied my idea of what I wanted to give a prize for. Others have apparently made as small or smaller marks, but no one tried to print an entire page. And on a 512 x 512 dot printer! Each dot is only about 60 atoms on a side. I can't quite manage to imagine the square 1/160 mm on a side onto which all that is printed. It would be 20 times too small on a side to see with the naked eye. Only ten wave lengths of light. The entire Encyclopaedia Britannica, perhaps 50,000 to 100,000 pages of your size would be on less than 2 mm on a side - the head of a small plain pin.

Your description of the square silicon nitride windows was a bit incomplete. How big are the windows? Is each window a page, or (less probably?) a letter? Can application to computers be far behind?

As promised long ago, I am enclosing a check for \$1,000 for your accomplishment.

Sincerely,

Richard P. Feynman

Richard P. Feynman

RPF;ht
encl.

**RICHARD P. FEYNMAN
GWENETH FEYNMAN**
797-1262
2475 BOULDER RD.
ALTADENA, CA 91001

16-66/1220

760

PAY TO THE ORDER OF

Thomas H. Newman DATE *Nov. 17, 1985* \$1000⁰⁰

One thousand and no/100 DOLLARS

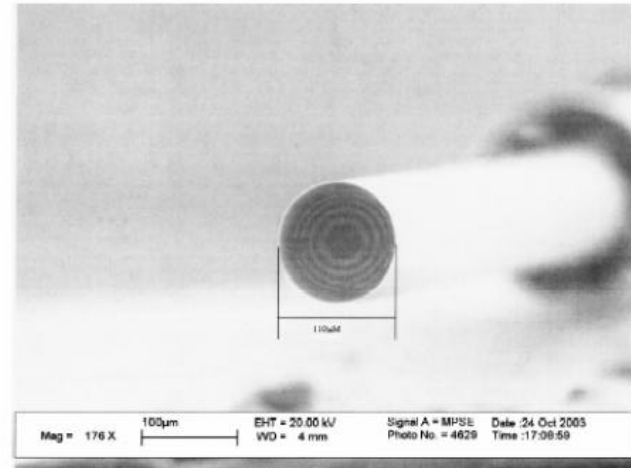
BANK OF AMERICA™
ALTADENA BRANCH 0291
2345 NORTH LAKE AVENUE
P.O. BOX 577
ALTADENA, CA 91001

Richard P. Feynman

Examples of More Flexible Tools

- High resolution EBL systems with tilt stages

- Lithography performed at the end of an optical fiber in an SEM by P. S. Kelkar *et al.* J. Vac. Sci. Technol. A **22**, 743 (2004)



- High resolution dedicated EBL systems with variable pressure chambers

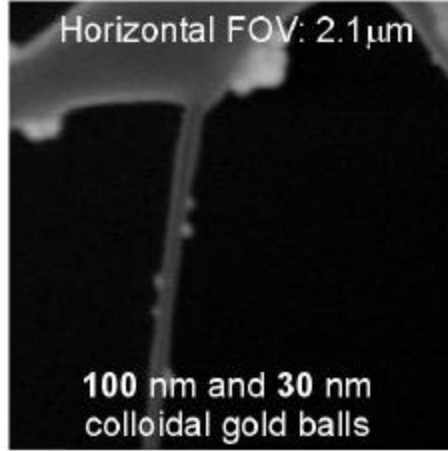
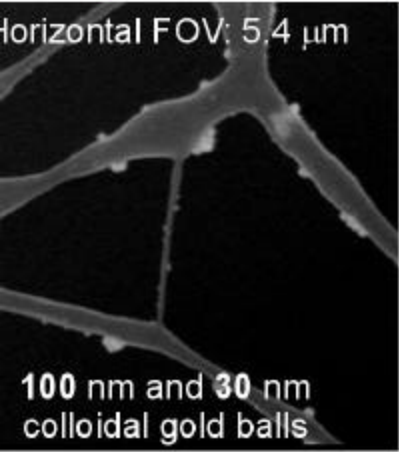
- Benefits already being explored for photomask CD metrology. For example, D.C. Joy Proc. SPIE Int. Soc. Opt. Eng. **5375**, 10 (2004)
- Simplify patterning of bulk insulators, SFIL templates, etc.

For $1\text{cm}^2/\text{s}$ EBL at 22nm we need distributed-axis electron optics

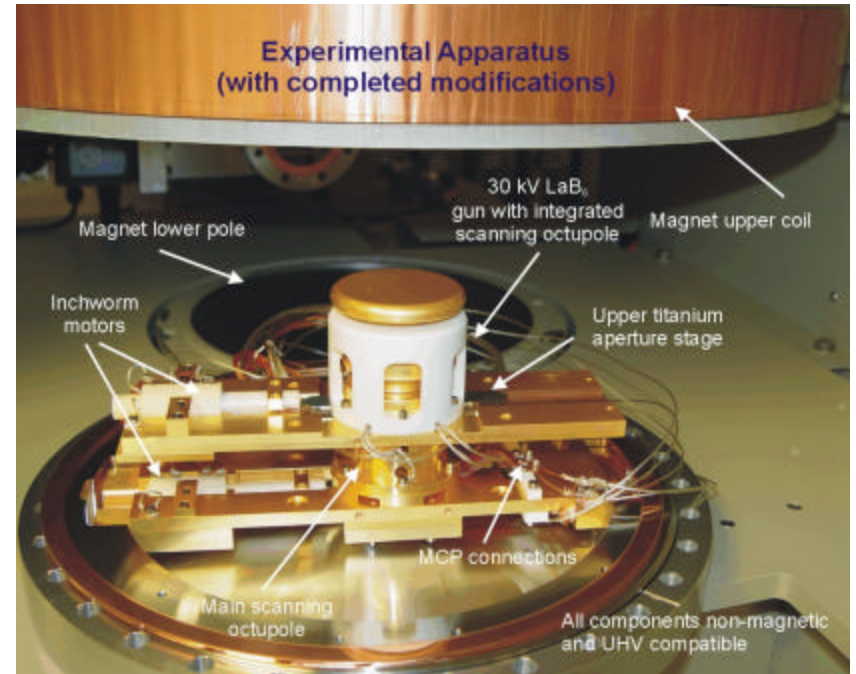
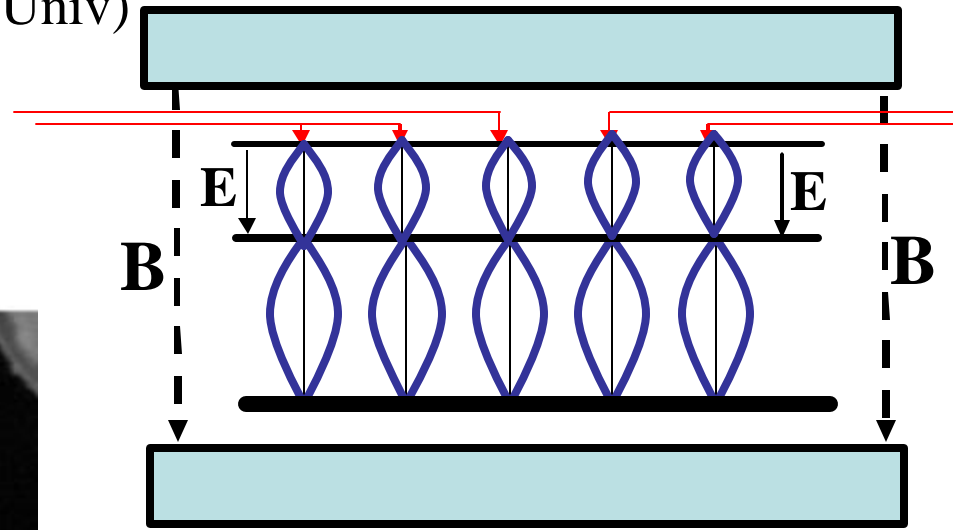
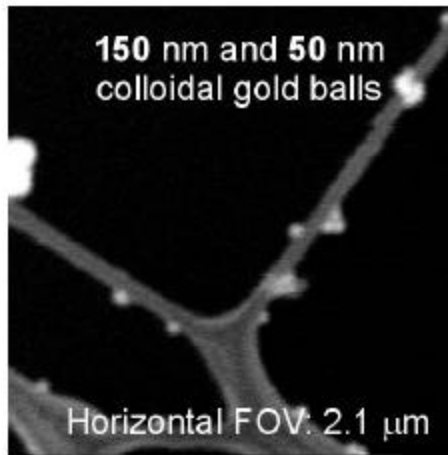
PIFA (Groves, Leica and Pickard, Stanford Univ)

High Resolution (below 50 nm) Imaging
(10 kV, 2 orbits)

100 nm and 30 nm colloidal gold balls:

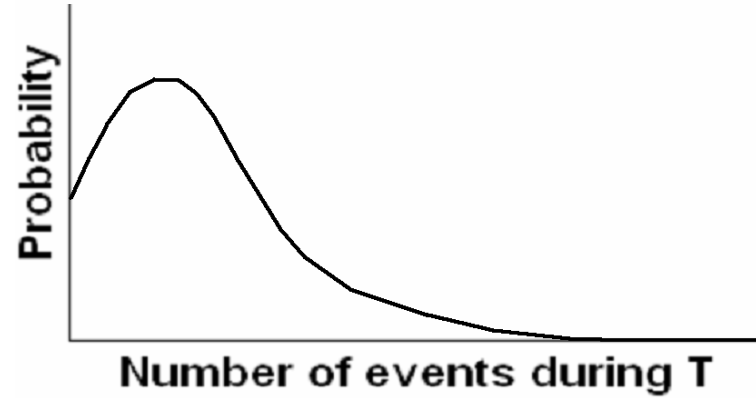
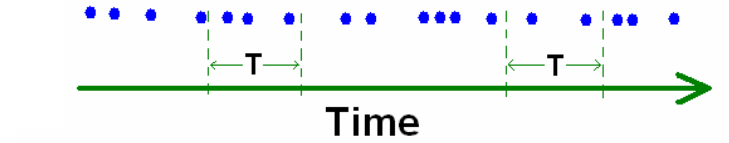
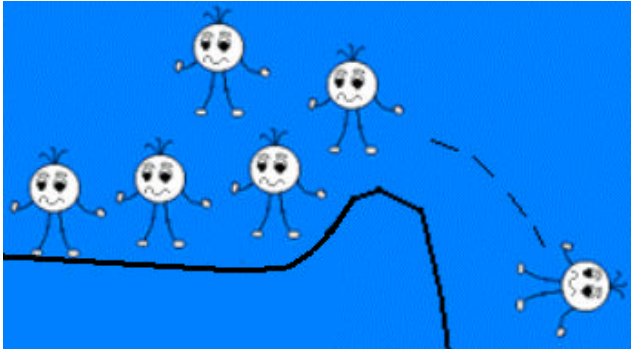


150 nm and 50 nm colloidal gold balls:

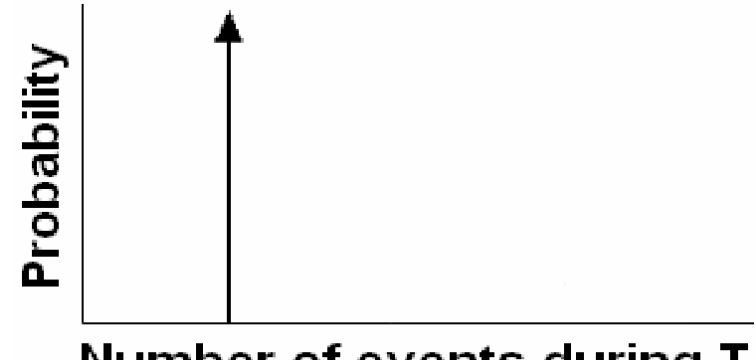
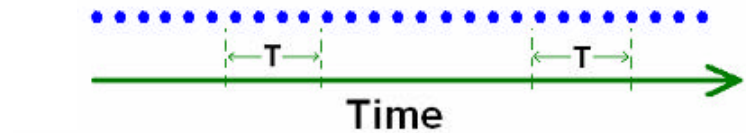
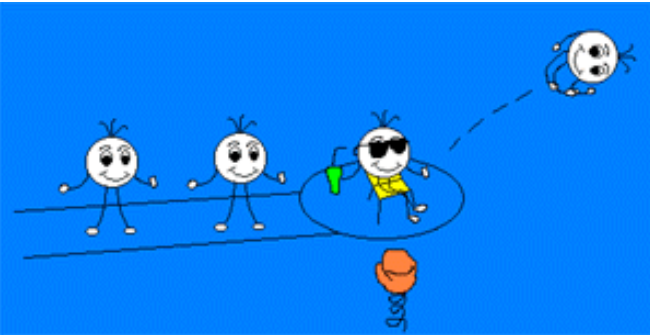


Shot noise

Random emission

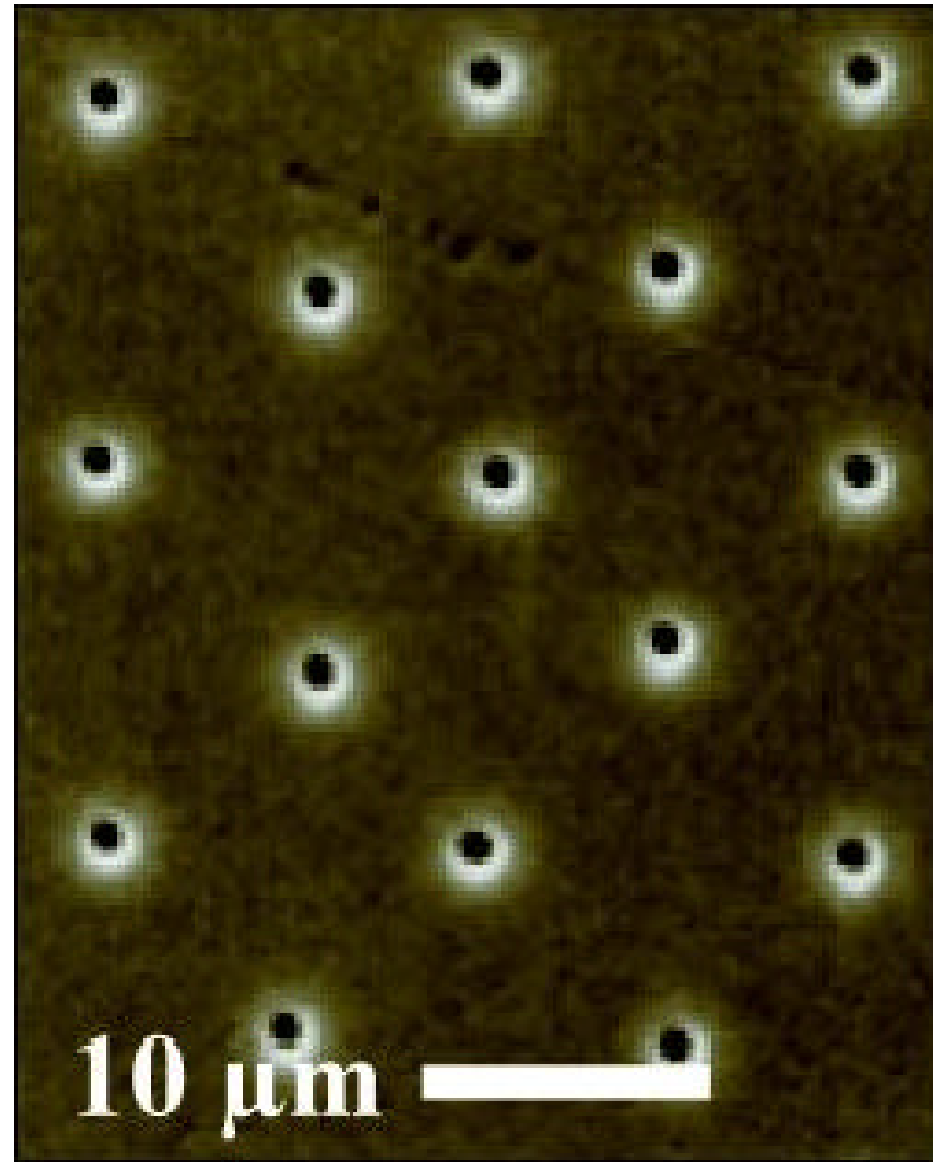
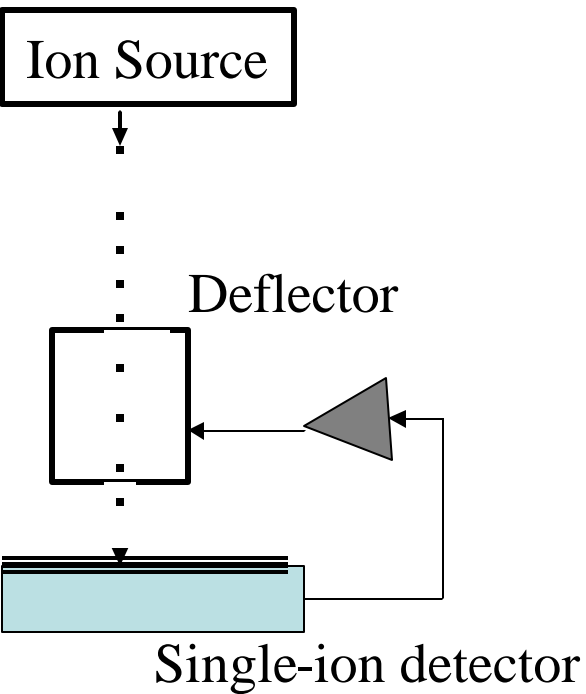


Turnstile emission



Opportunity: Do something about the shot noise: realize the single-quantum feature

FIB exposure:
moved 'beam position' after
monitoring 1 ion landing.

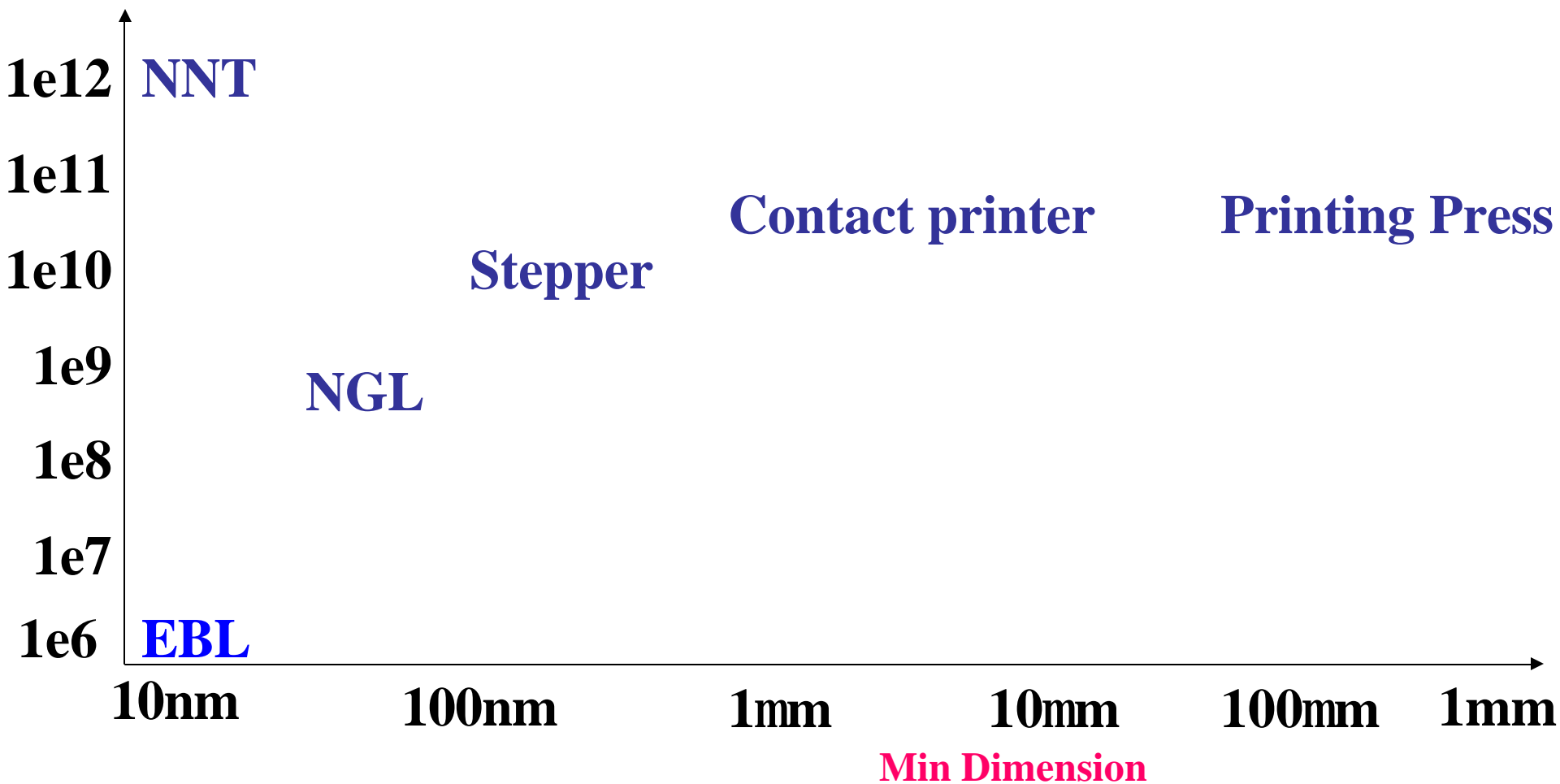


Europhysics News (2004) Vol. 35 No. 5
Ion tracks – a new route to nanotechnology

Alois Weidinger, Hahn Meitner Institute Berlin, Berlin, Germany



#MFS/second



Intel / Princeton

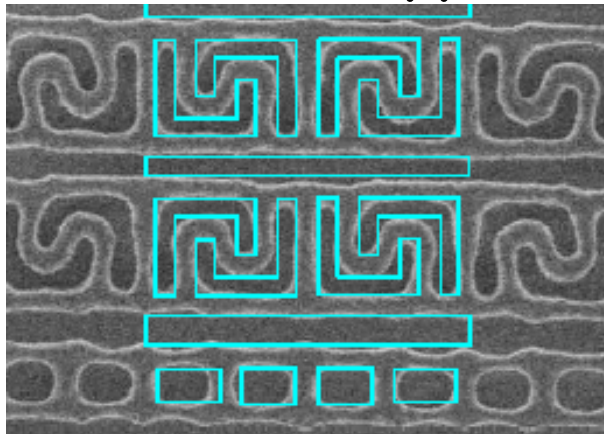
Intel

Princeton

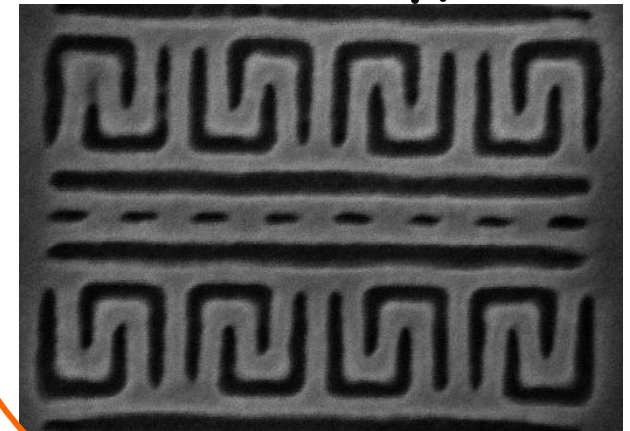
1.13 μm^2 cell by 193 nm lithography & phase masks (2002)

0.04 μm^2 cell by nanoimprint lithography

110 nm Half-Pitch



20 nm Half-Pitch



Reduction:

- 6X in linear
- 30X in area

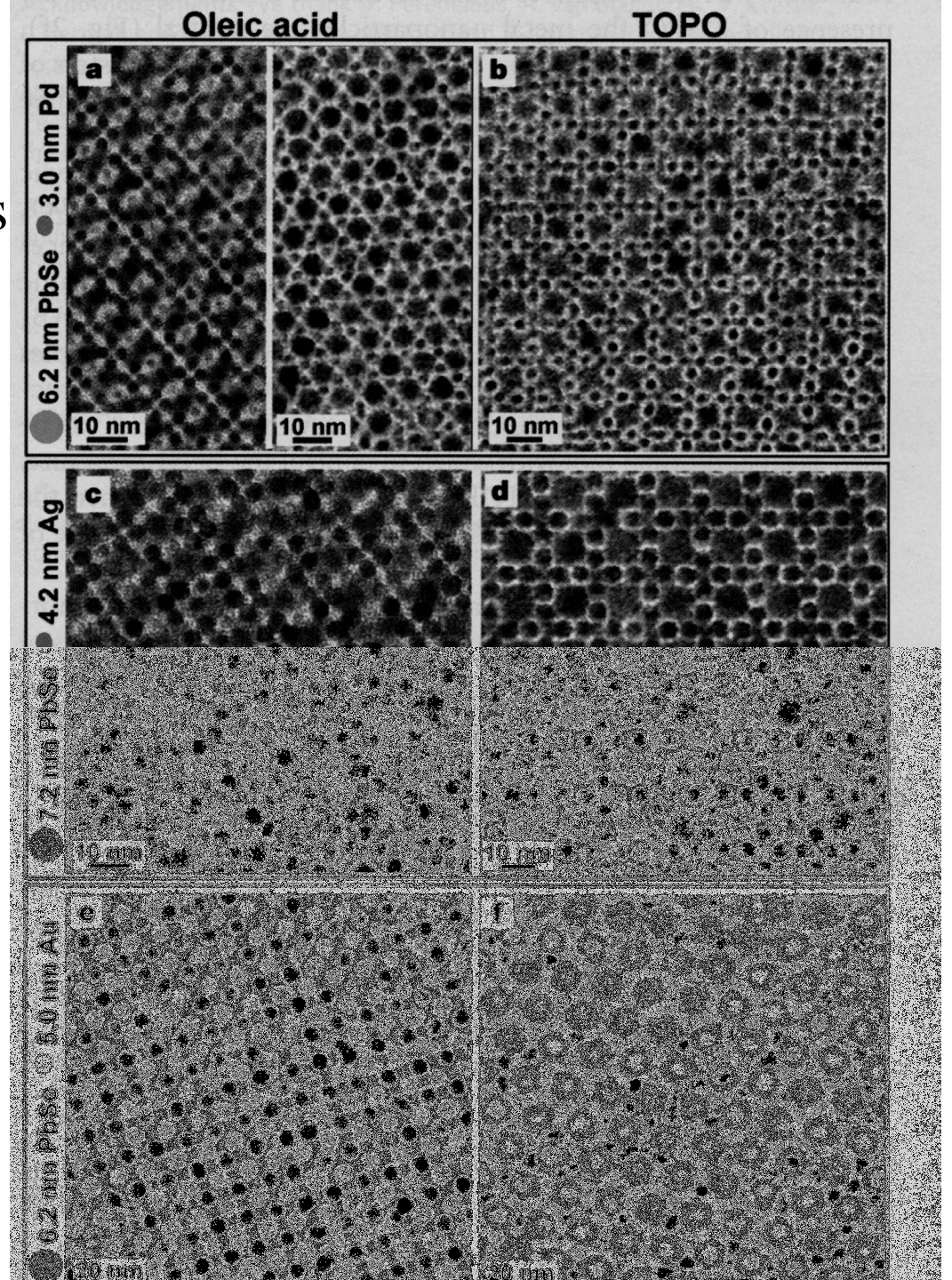
<ftp://download.intel.com/research/silicon/BorodovskyPhotomaskJapan0402pres.pdf>

Austin and Chou to be published
Nanonex NX-2000 NIL machines
Nanonex NXR-2010 resist

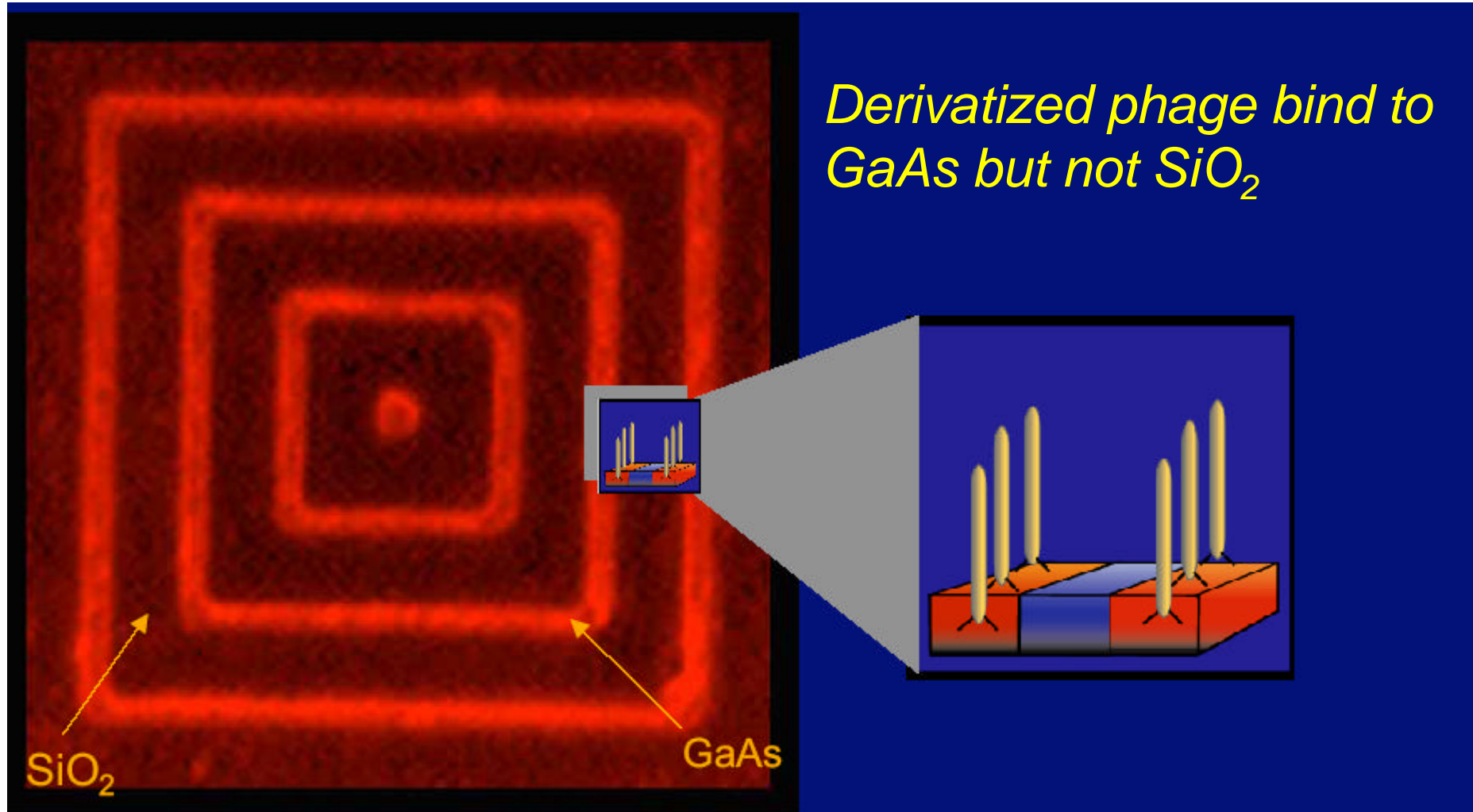
Shevchenko et al.

Nature, **439**, 5Jan2006, p.55

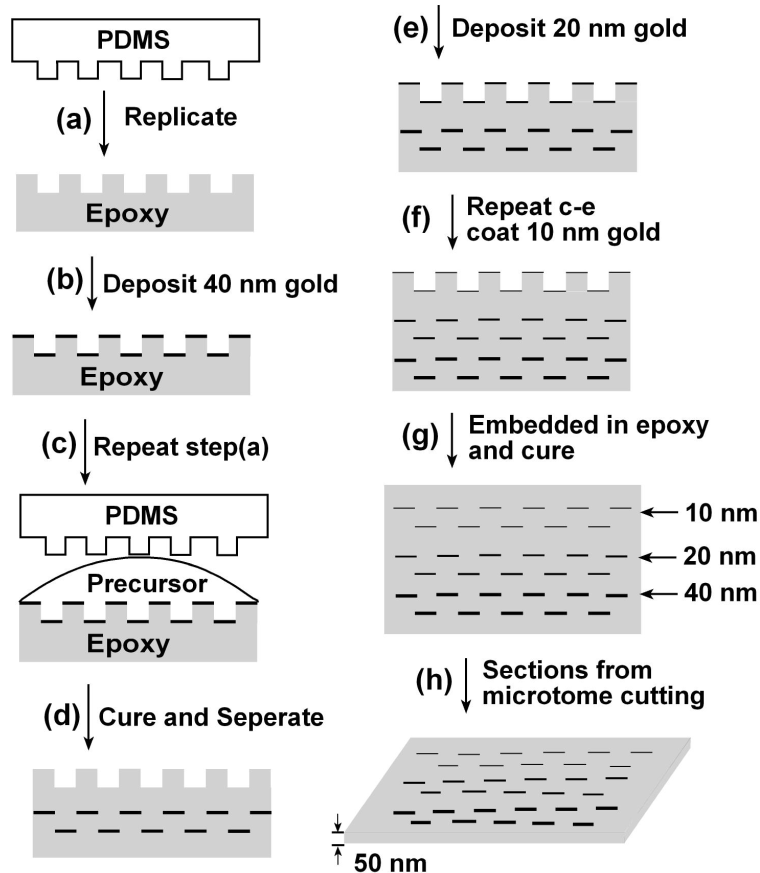
Binary Nanoscale Superlattices



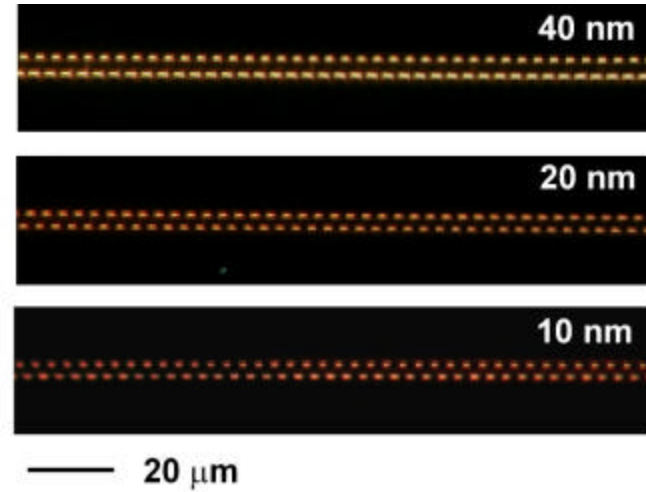
Binding Agents Are Highly Specific



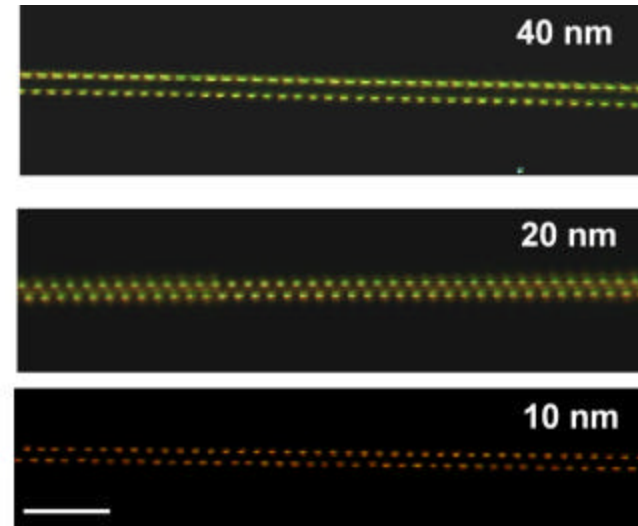
Sectioning as a route to nanostructures...



100 nm section



50 nm section



Conclusions

- Very low volume nanofabrication is well established,
- Manufacturing at the nanoscale presents major challenges: pattern generation, economic throughput, placement, assured freedom from defects,
- There are many opportunities for improvement. New ideas are continually emerging. They need a disciplined approach.