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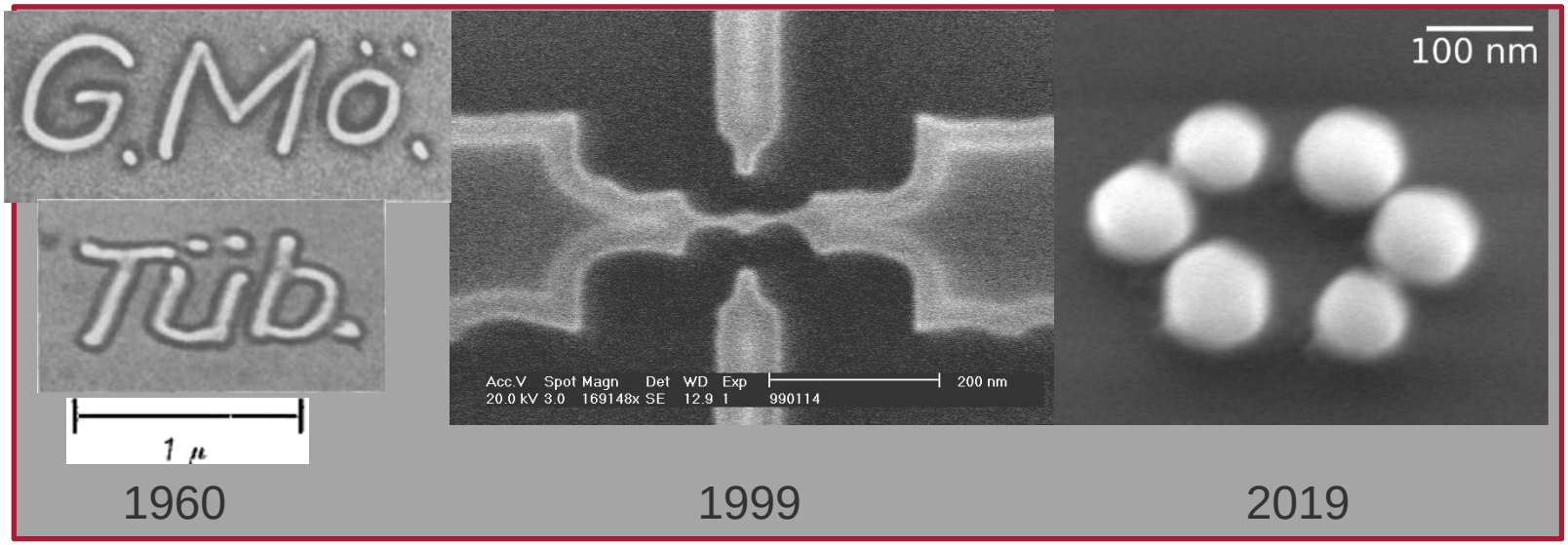
UNIVERSITÄT
TÜBINGEN

Faculty of Science
Department of Physics/Institute for Applied Physics
Nanostructures and Nanofabrication
LISA+ Center for Light-Matter Interaction, Sensors & Analytics



EBL at age 65 – a retrospect

Dieter P. Kern

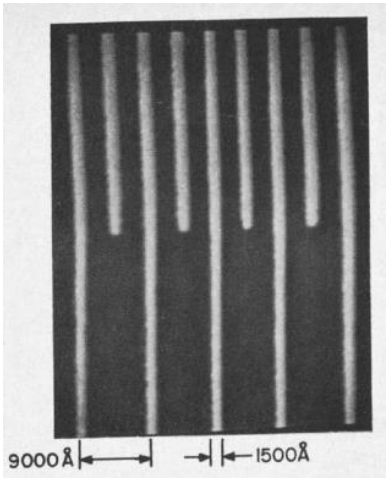
BEAMeeting Munich 2025

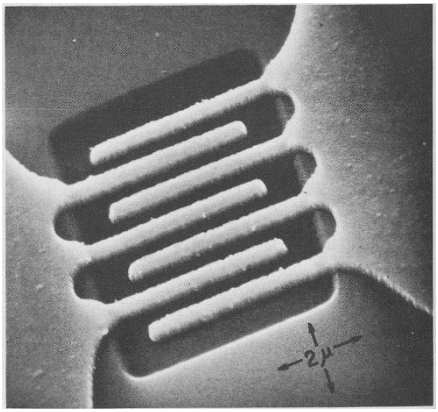
Main Driver: Miniaturization of electronics

- Late 1960s: first resist exposures on Si with electron beams (PMMA, M. Hatzakis, 1968)
- Early 1970s: first e-beam machines, enabling real devices smaller than 5µm (by many perceived as limit for optical lithography at the time)
- But also early diversification: SAW-devices, x-ray optics,…

150nm Al electrodes on SAW transducer

E. G. Lean and A. N. Broers, Microwave Journal (1970) Vol. 13, pp. 97-101





0.5µm metal contacts and spaces on transistor

M. Hatzakis, J. Electrochem. Soc. 116 1033, (1969)

Main Driver: Miniaturization of electronics

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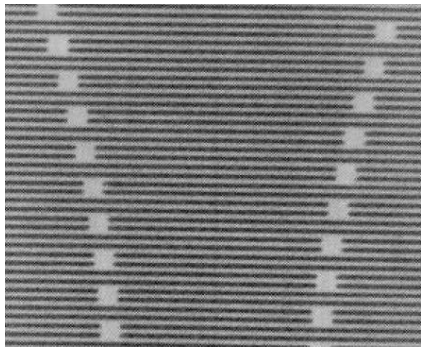
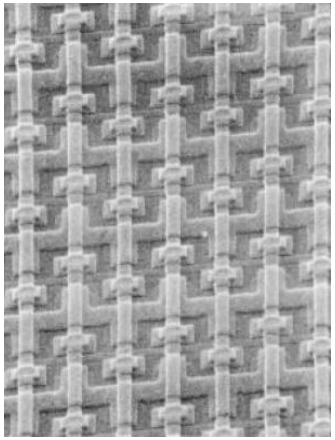


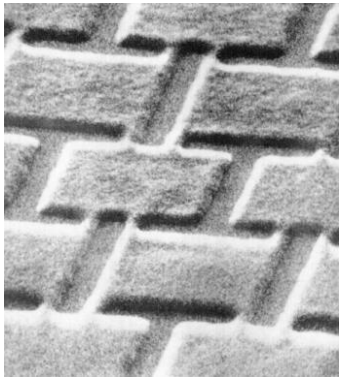
SAW filter with1.2µm lines and spaces

F. S. Ozdemir, W. E. Perkins, R. Yim, and E. D. Wolf, J. Vac. Sci. Technol. (1973) Vol. 10, p. 1008



8K FET memory wit 1µm minimum feature

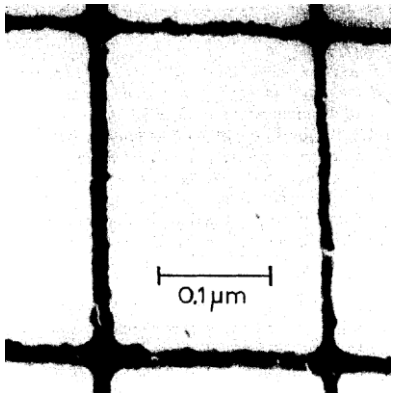
A. J. Speth, A. D. Wilson, A. Kern, and T. H. P. Chang, J. Vac. Sci. Technol. (1975) Vol. 12, p 1235



Bubble memory pattern with 0.25µm lines and 0.1µm gaps

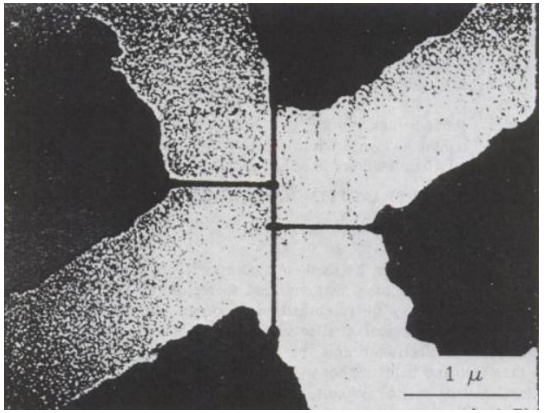
Testing limits for miniaturization of electronics

- Mid 1970s: first fundamental studies on real nanostructures associated with electronic problems



8nm Au/Pd wires on carbon foil

A. N. Broers, W.W. Molzen, J. J. Cuomo, and N. D. Wittels (1976) Appl. Phys. Lett 29, 596



25nm Nb wire in 4-point configuration

R. B. Laibowitz, A. N. Broers, J. T. C. Yeh, and J. M. Viggiano, (1979) Appl. Phys. Lett. 35, 891

fabricated using electron beam “contamination – writing” and ion milling

Most beautiful experiment: Claus Jönsson's multiple slits for electrons

Fabrication by contamination lithography and electroplating of Cu

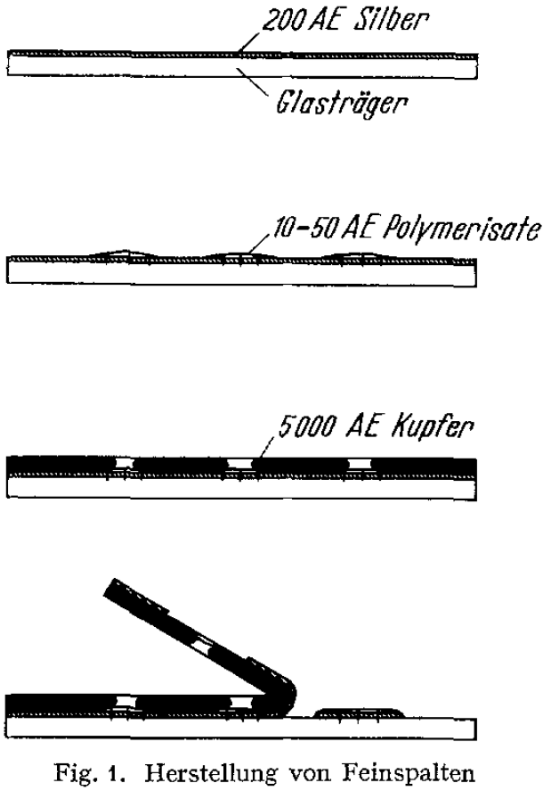
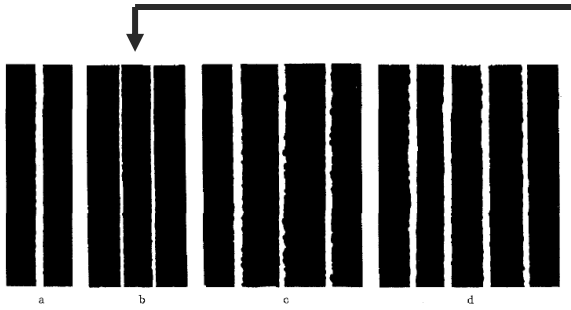
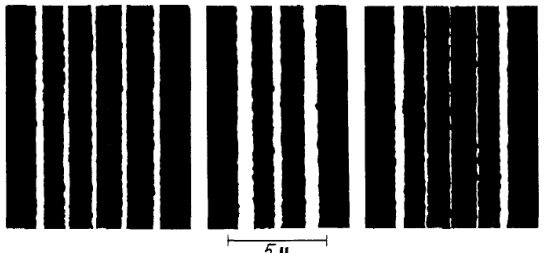


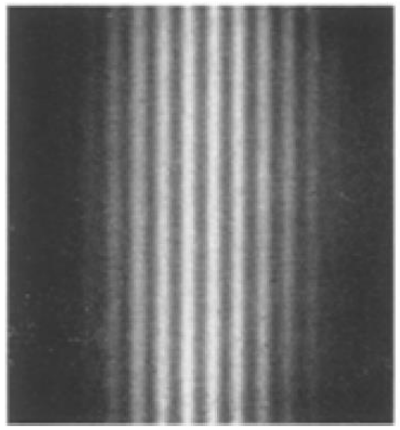
Fig. 1. Herstellung von Feinspalten

C. Jönsson, Z. Physik 164 (1961) 454



100nm slits, 1.2µm apart





Electron diffraction from 2 slits

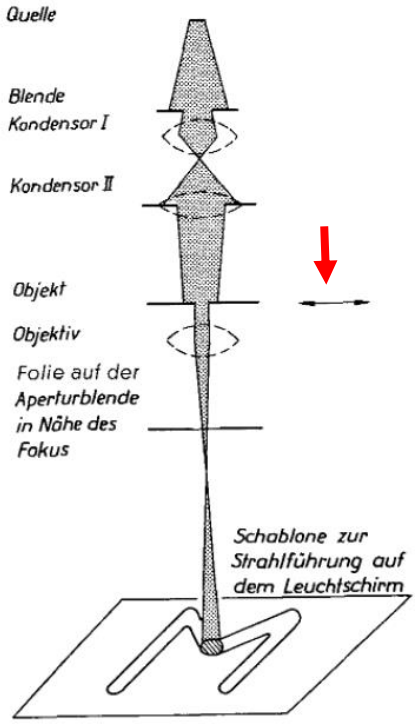
First Electron Beam Lithography

- Early attempts

50nm linewidth in collodion

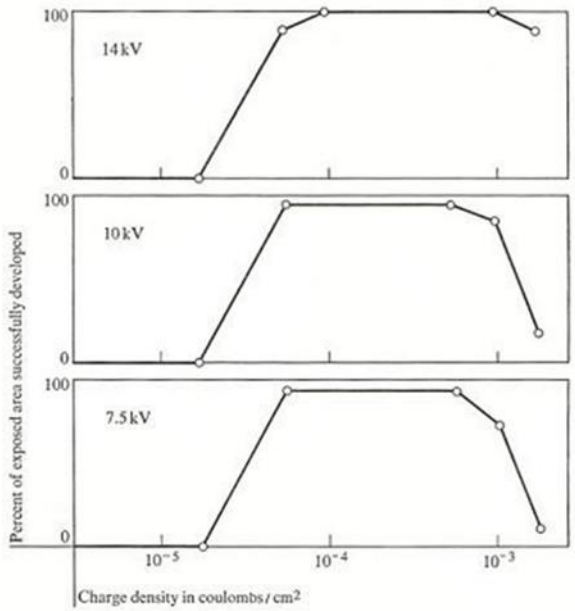
G.Möllenstedt, R. Speidel,
Phys. Blätter 16, 192 (1960)

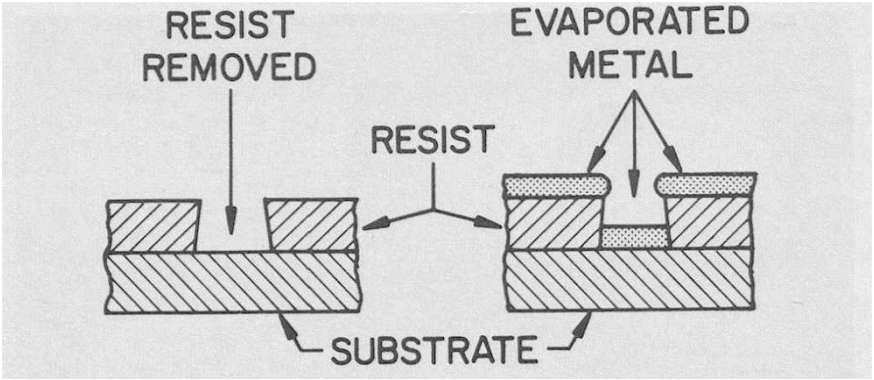
manual operation!



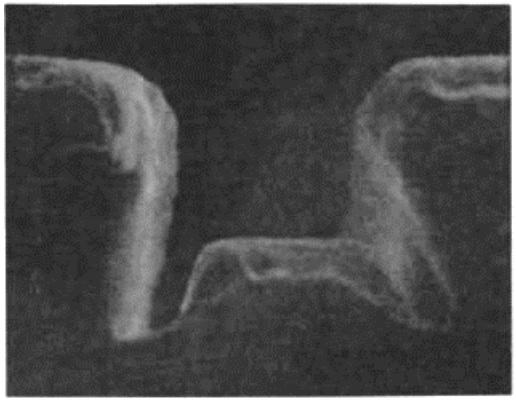
29.12.1959, Caltech
“There is plenty of room at the bottom”, R. Feynmann

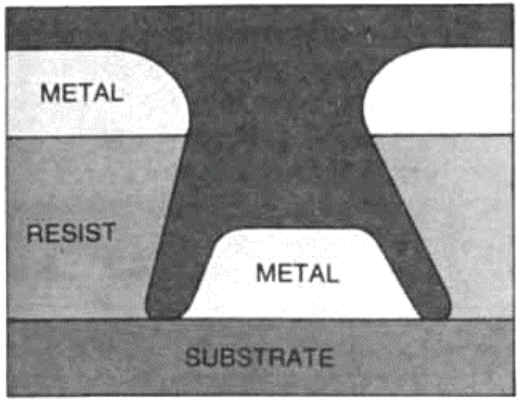
Finally: PMMA, a high resolution electron beam resist





First PMMA contrast curves and lift-off principle



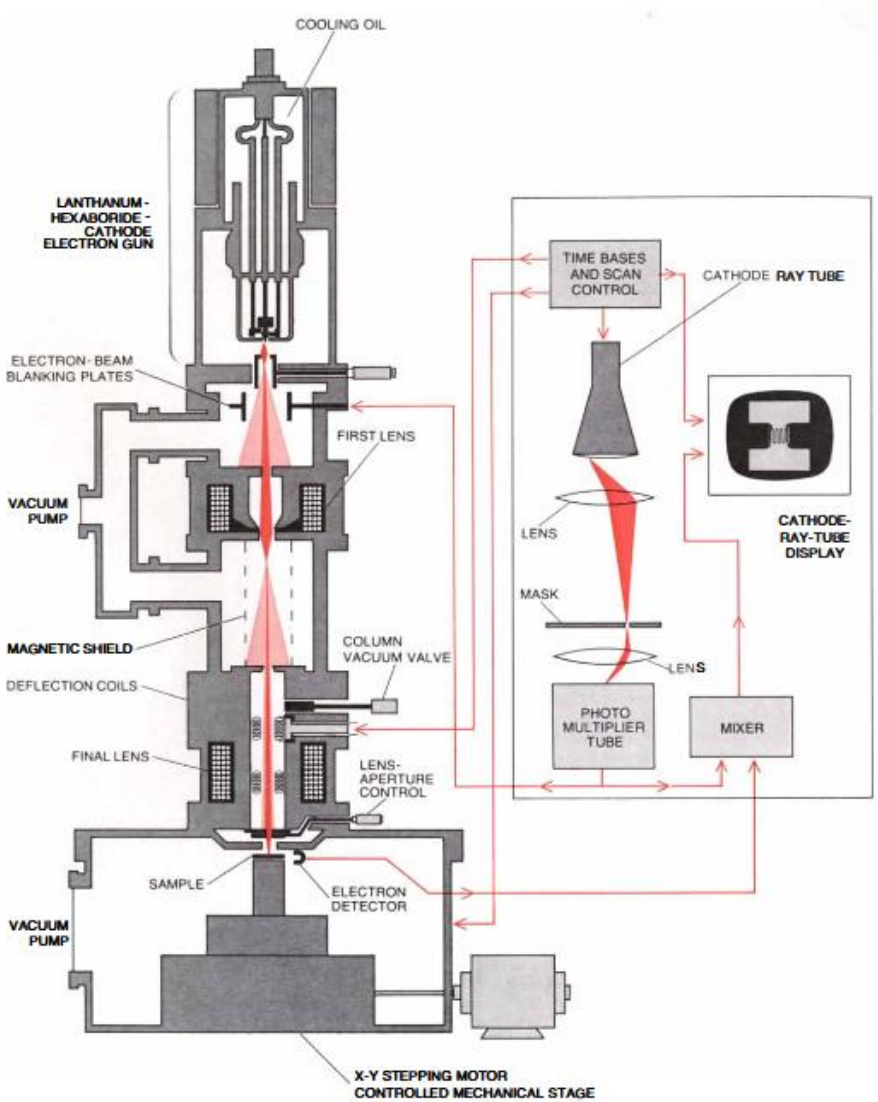


I. I. Haller; M. Hatzakis; R. Srinivasan, High-resolution Positive Resists for Electron-beam Exposure, IBM Journ. Res. Dev., 12, 251, (1968)

II. M. Hatzakis, Electron Resists for Microcircuit and Mask Production, J. Electrochem. Soc. 116 1033, (1969)

III. A. N. Broers and M. Hatzakis, Microcircuits by electron beam, Sci. American 227 34-48 (1972)

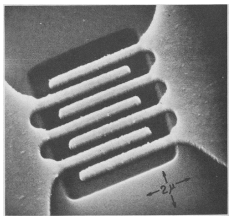
A period of lithography systems development



Early 2-lens Gaussian beam system with

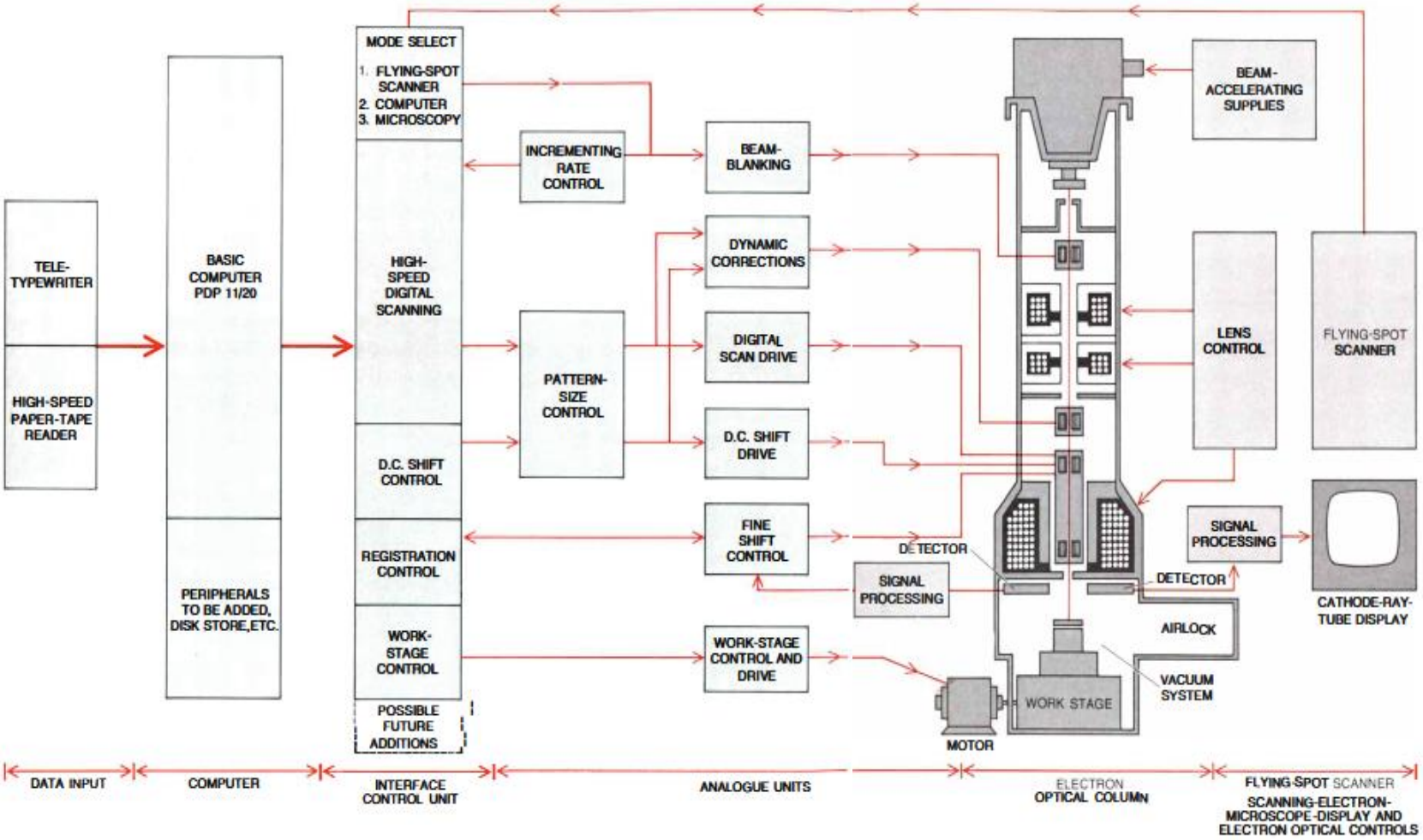
Flying Spot Scanner as pattern data source

Used by M. Hatzakis in 1969 to fabricate 0.5μm planar bipolar transistor



From: A. N. Broers and M. Hatzakis, Microcircuits by electron beam, Sci. American 227 34-48 (1972)

"Next Generation" early system (1972)



Schematic of system developed at Cambridge Instruments, became base of many followers, e.g. IBM Vectorscans

From: A. N. Broers and M. Hatzakis, Microcircuits by electron beam, Sci. American 227 34-48 (1972)

A period of lithography systems development

In the 1970‘s and early 1980’s significant efforts in electron beam lithography systems development started

In the labs of microelectronics companies, e.g. Bell Labs, IBM, TI, HP, Hughes, Hitachi, Toshiba, Thomson CSF, Philips, ….

But also with equipment manufacturers, e.g. Cambridge Instruments, JEOL, …

The applications were primarily research and development, experimental support of the device scaling efforts of the time

Mask making and potential for manufacturing were explored.

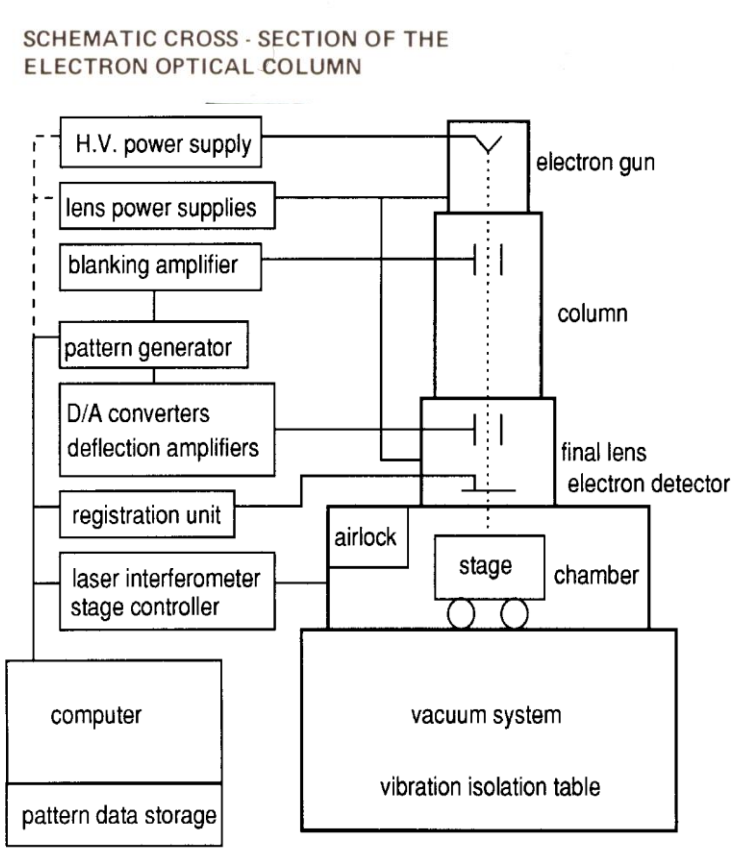
A period of lithography systems development

Main areas of development (to list a few):

Electron optics:	electron source, from W to LaB_6 eventually to thermal field emitters
	low aberration deflection arrangements, e.g. double deflectors with properly rotated second coil for reduced deflection aberrations, octupole deflectors, variable axis lens, electro-”static” subfield deflectors, high-resistivity ferrite polepieces to eliminate eddy currents, …
Precision:	Laser controlled tables for metrology position error feedback on deflection electromagnetic shielding
Digital control:	pattern data preparation and handling multiple correction paths increase deflection rates

„Generic“ electron beam system of the late 1970‘s

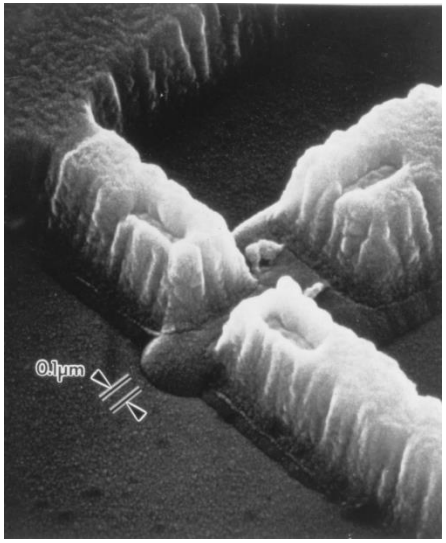
IBM / Tübingen University

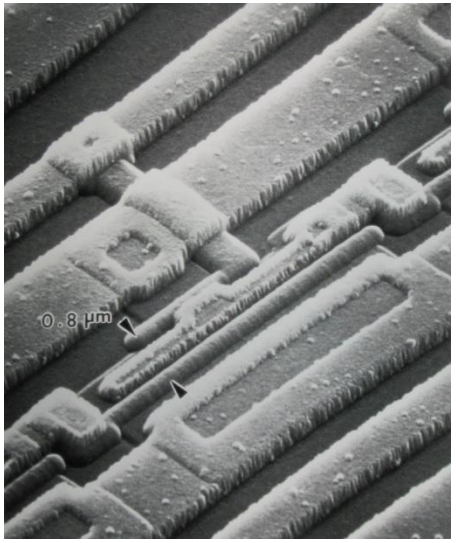


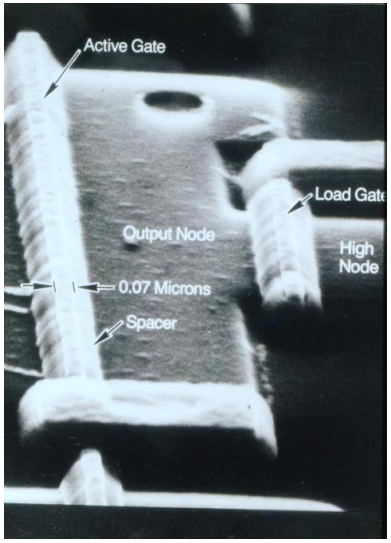
Typical Gaussian beam system

(with partly 70s and 80s technology)

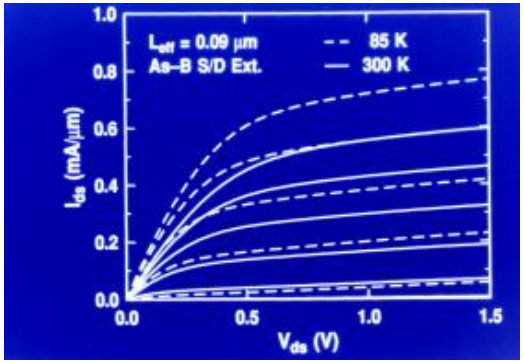
Exploratory device and circuit technology

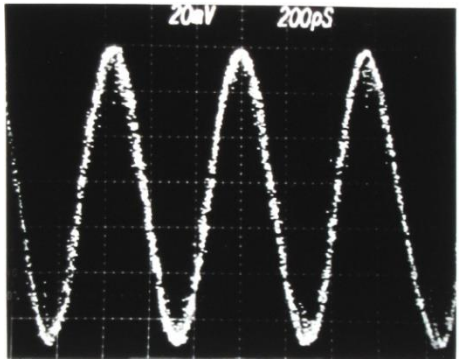






IBM 1987: <100nm n-FET, 4 levels all e-beam, <30nm overlay





g_{max}= 1S/mm

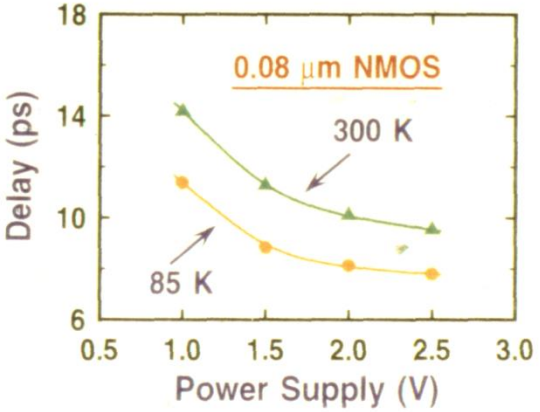
21 stage ring oscillator
13.1 ps delay per stage

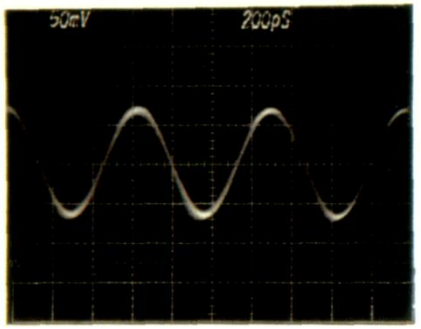
(85 K, 1.7V V_{DD})

IEEE Electron Device Letters, EDL-8 (1987) 463-466, J. Vac. Sci. Technol. B6 (1988) 140-145

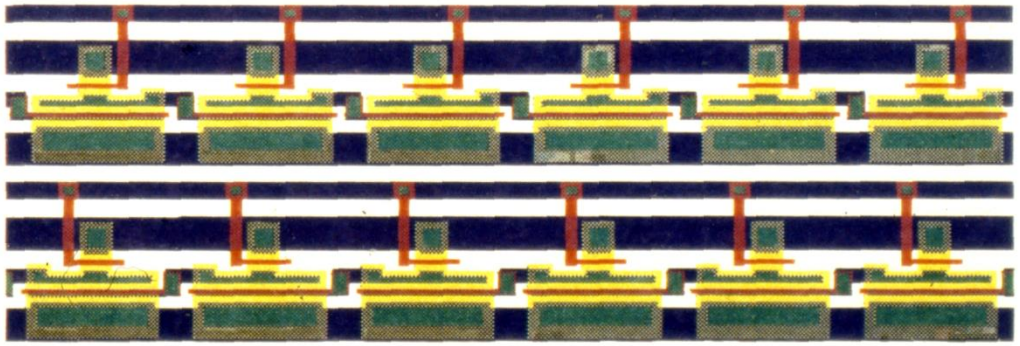
Fastest Switching in Silicon (in 1993)

7.8 ps at 85 K





Ring Oscillator Waveform



Ring Oscillator Layout

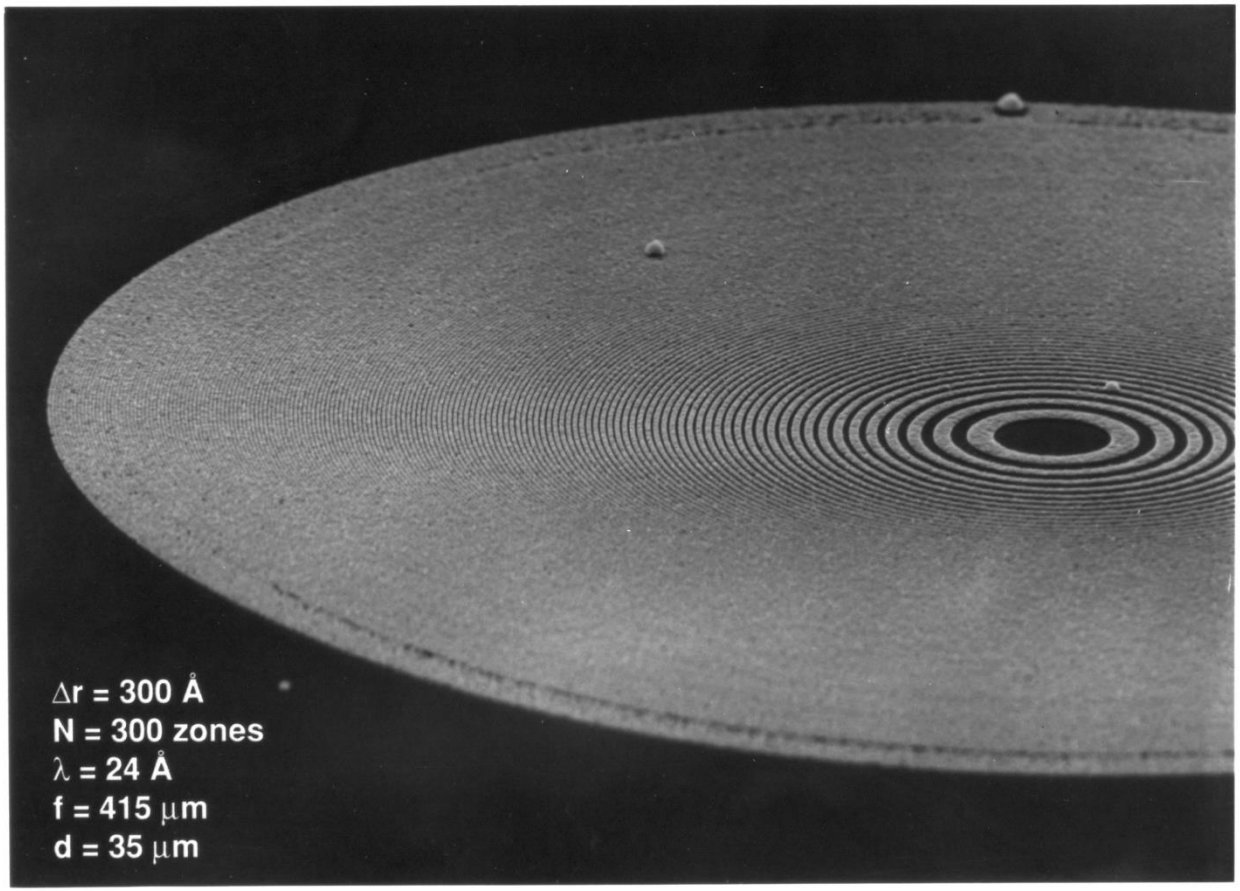
Y.J. Mii, S. Rishton, Y. Taur, D.P. Kern, T. Lii, K. Lee, K.A. Jenkins, D. Quinlan, T. Brown Jr., D. Danner, F. Sewell, M. Polcari, Experimental High Performance Sub-0.1µm Channel nMOSFET's, IEEE Electron Device Letters EDL15 (1994) 28

IBM

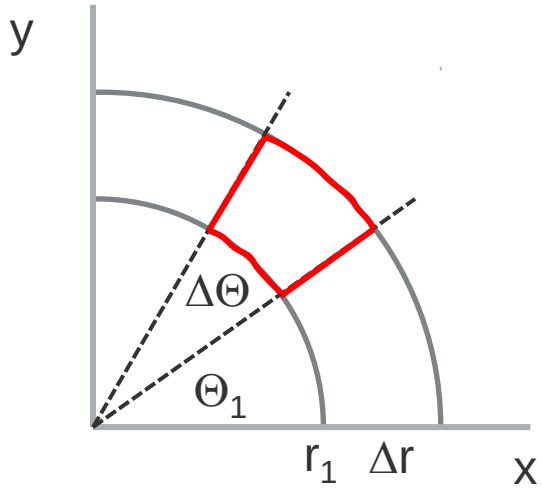
Diversification: x-ray optics

IBM

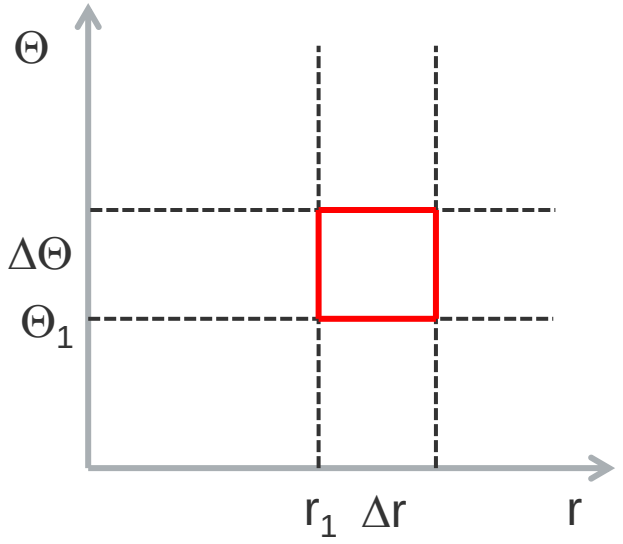
New 300 Å Gold Zone Plate Lens



Real time Cartesian to Polar coordinates conversion



beam



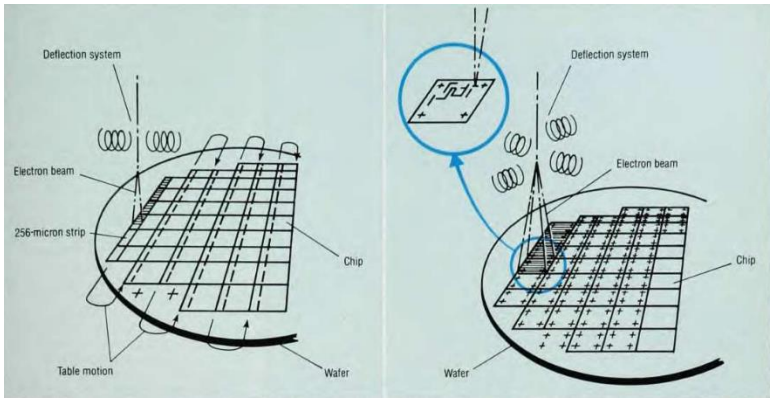
pattern generator

An example of an update to a rectilinear pattern generator to meet new requirements regarding shapes and data volumes

Further e-beam system evolution

So far: **Gaussian Beam systems**

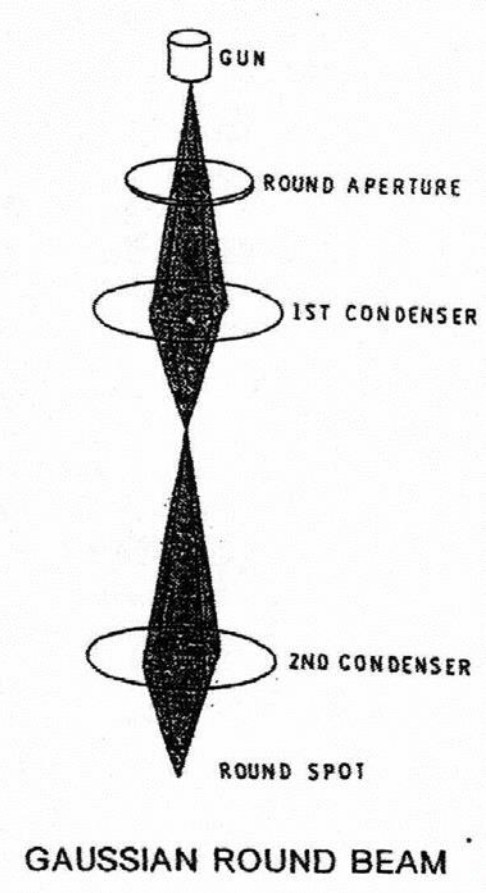
Two operating modes:



raster scan	vector scan
1-d scan	2-d scan
simpler	more flexible

\+ flexible, very high resolution

\- **Slow (pixel by pixel)**



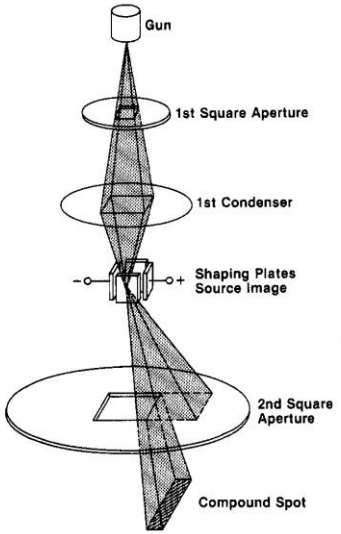
Evolution to variable shaped beam

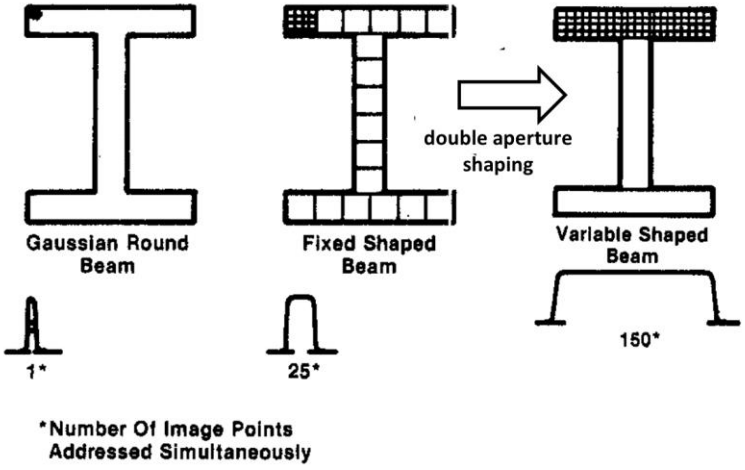
evolution from

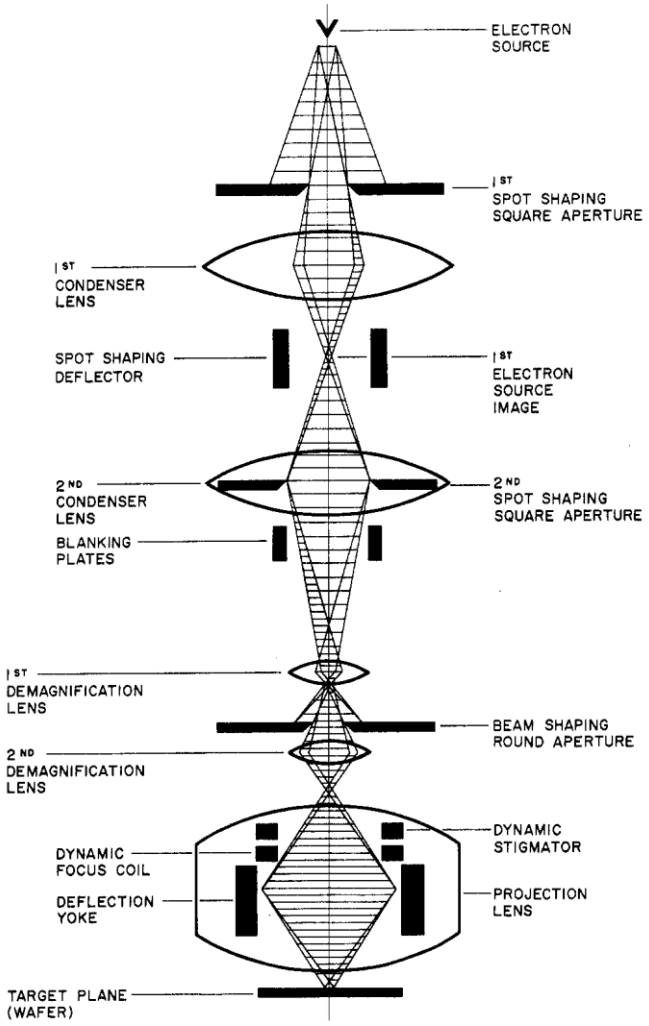
single Gaussian beam

to

variable shaped beam

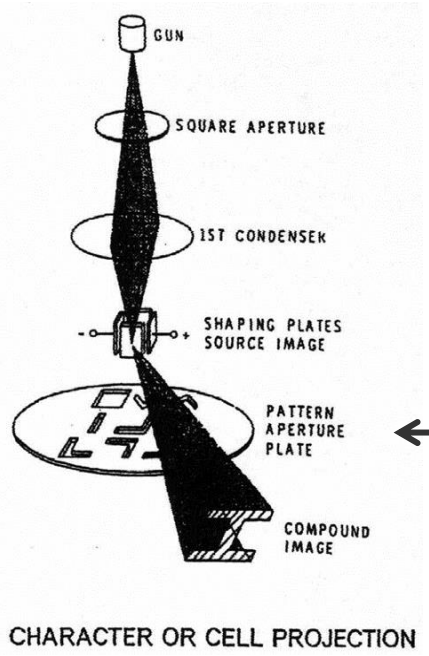




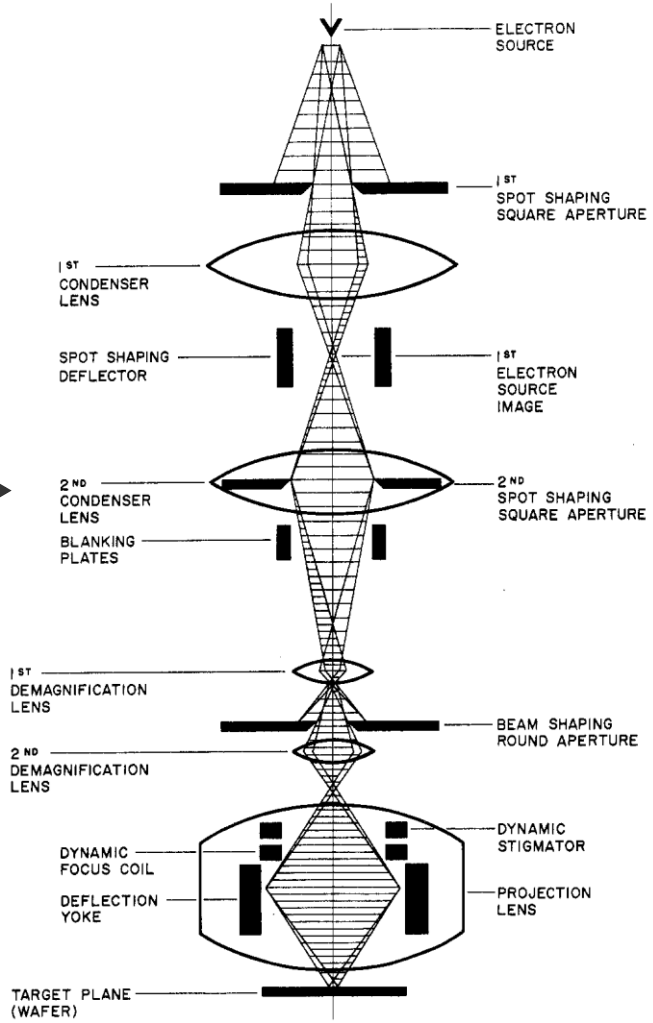


After H.C. Pfeiffer, IEEE Trans. Electron Devices ED26, 663 (1979)

Evolution to character or cell projection



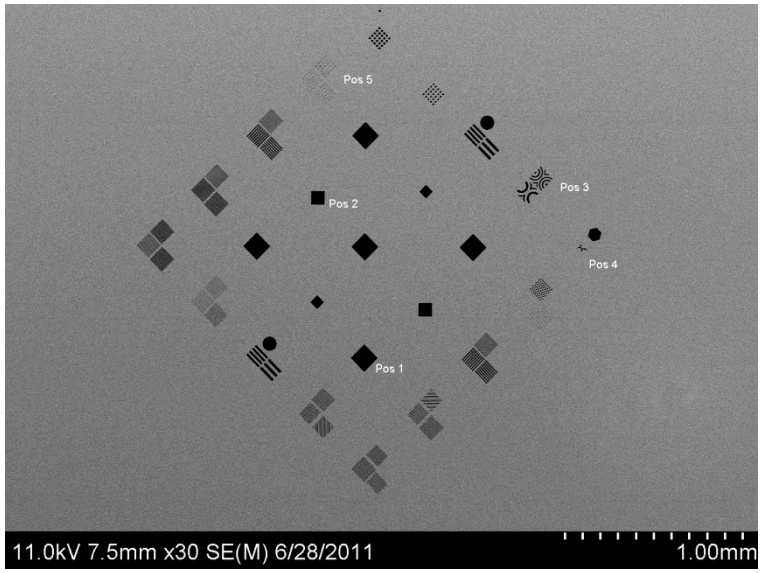
CHARACTER OR CELL PROJECTION

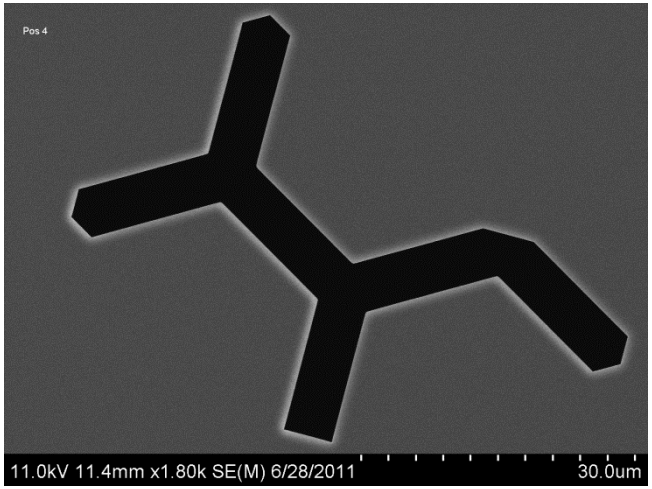


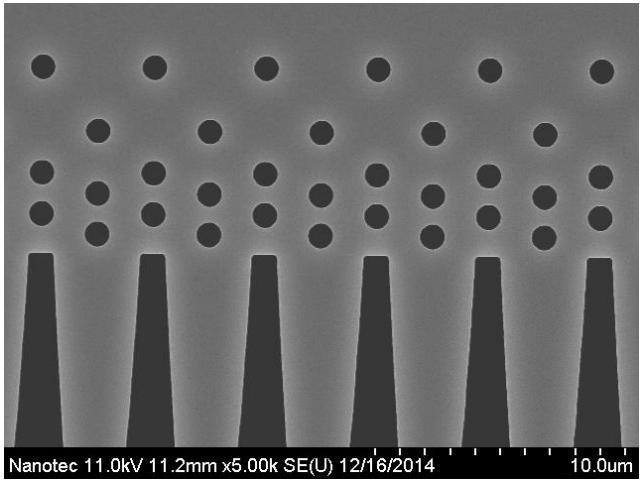
Character or cell projection:

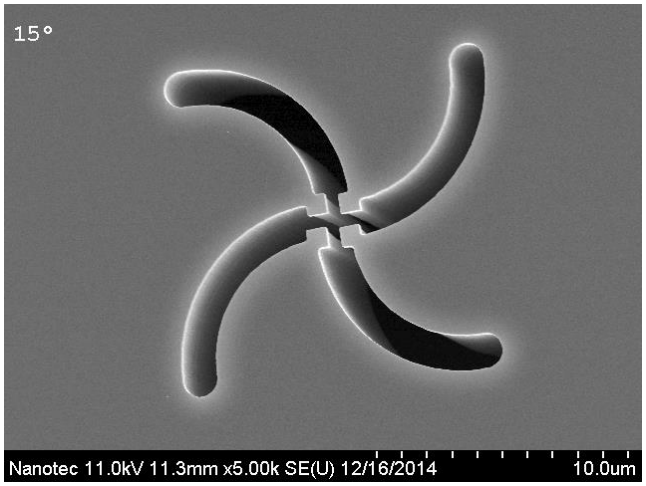
replace 2nd shaping aperture by plate with multiple shapes (e.g. silicon membrane)

Example-Reticle for Cell-Projection



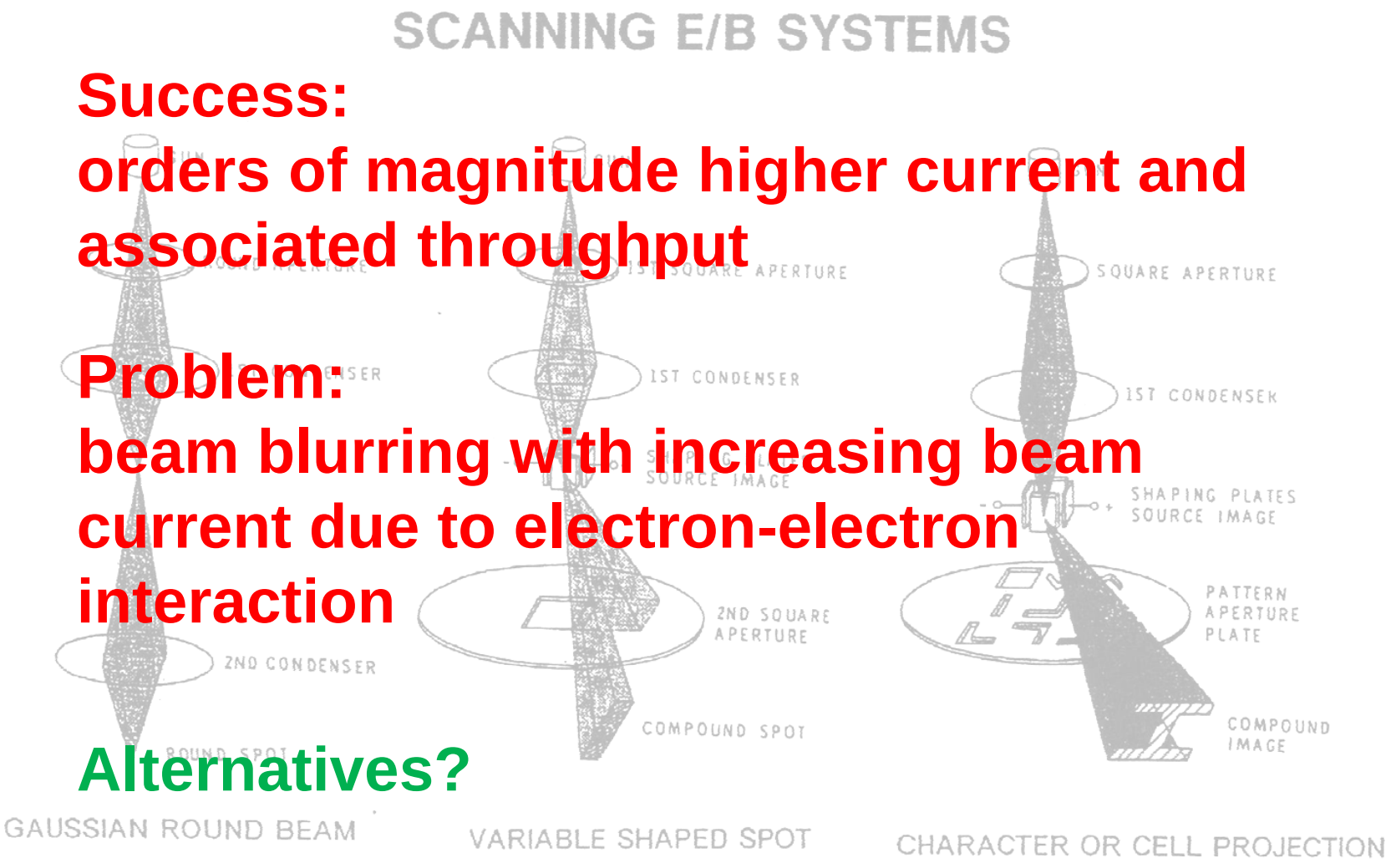






Courtesy Team Nanotech

E-beam evolution



Success:
orders of magnitude higher current and associated throughput

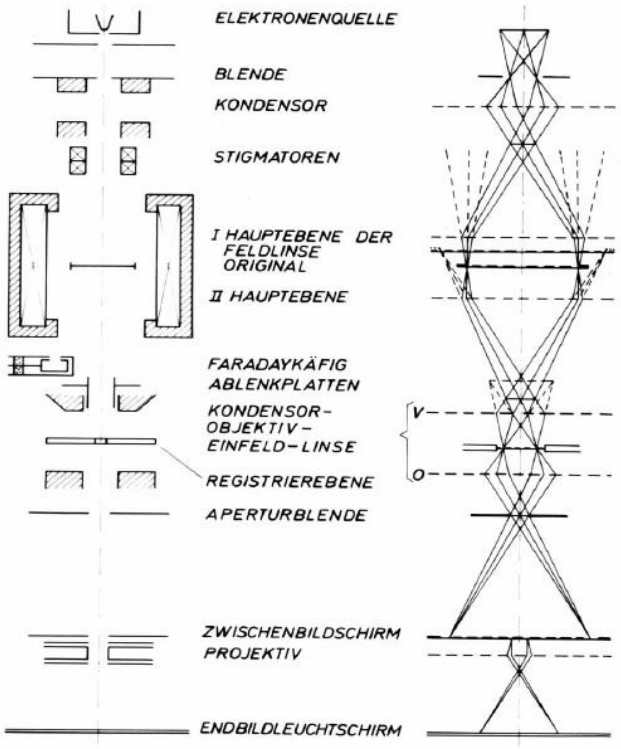
Problem:
beam blurring with increasing beam current due to electron-electron interaction

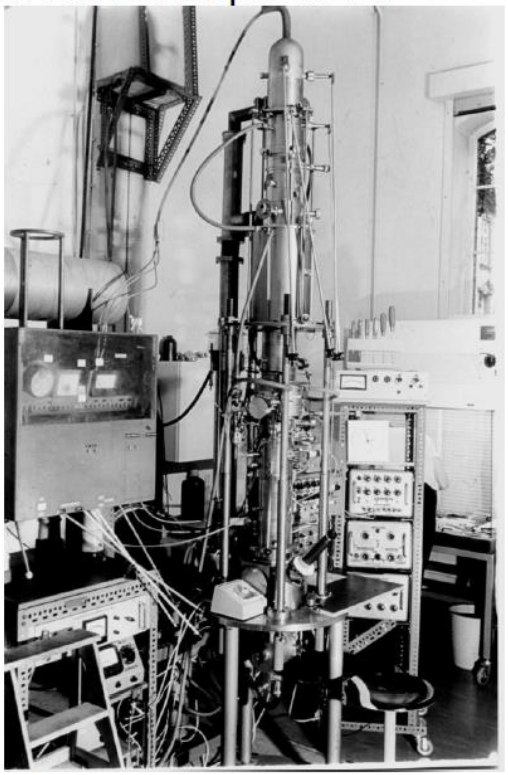
Alternatives?

E-beam evolution: projection systems

Reducing Image Projection with electrons for 100 nm pitch

1966-1971 at IAP-University Tübingen Diss. Koops **1971**

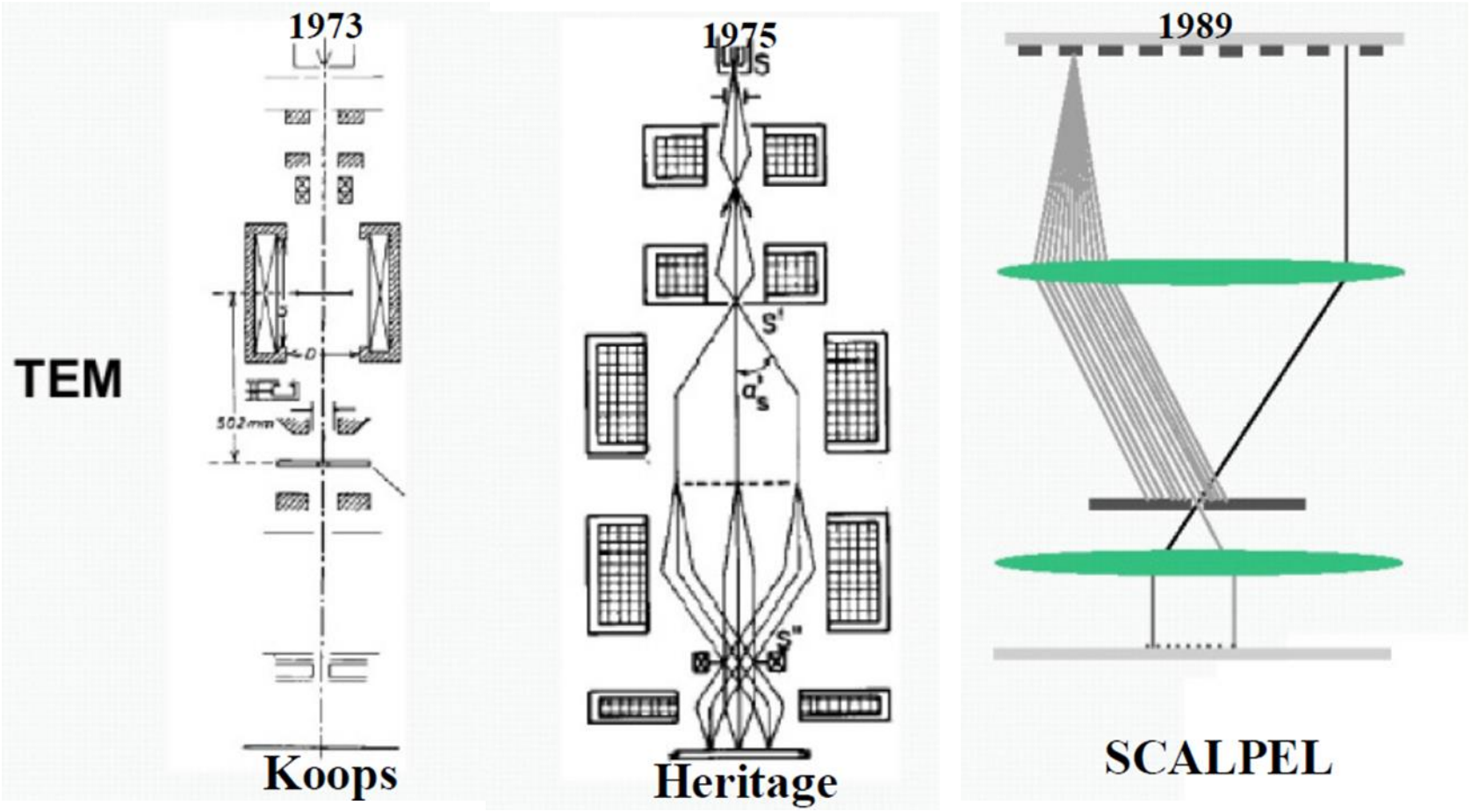




120:1, 40 kV, mask diameter 40 mm, resolution 30 nm, optical and magnetic / electrostatic monitoring electron microscope, distortion < 1.5%

H. Koops, J. Vac. Sci. Technol. 10 (1973) 909

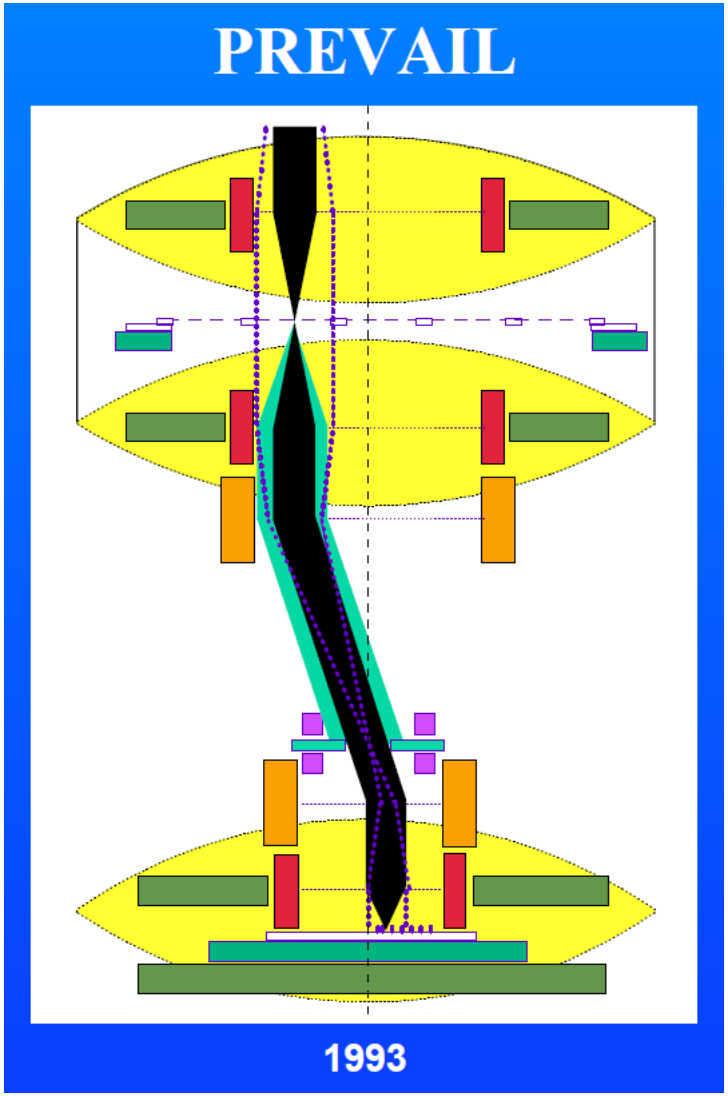
E-beam evolution: projection systems



absorbing mask

scattering mask

E-beam evolution: PREVAIL principle



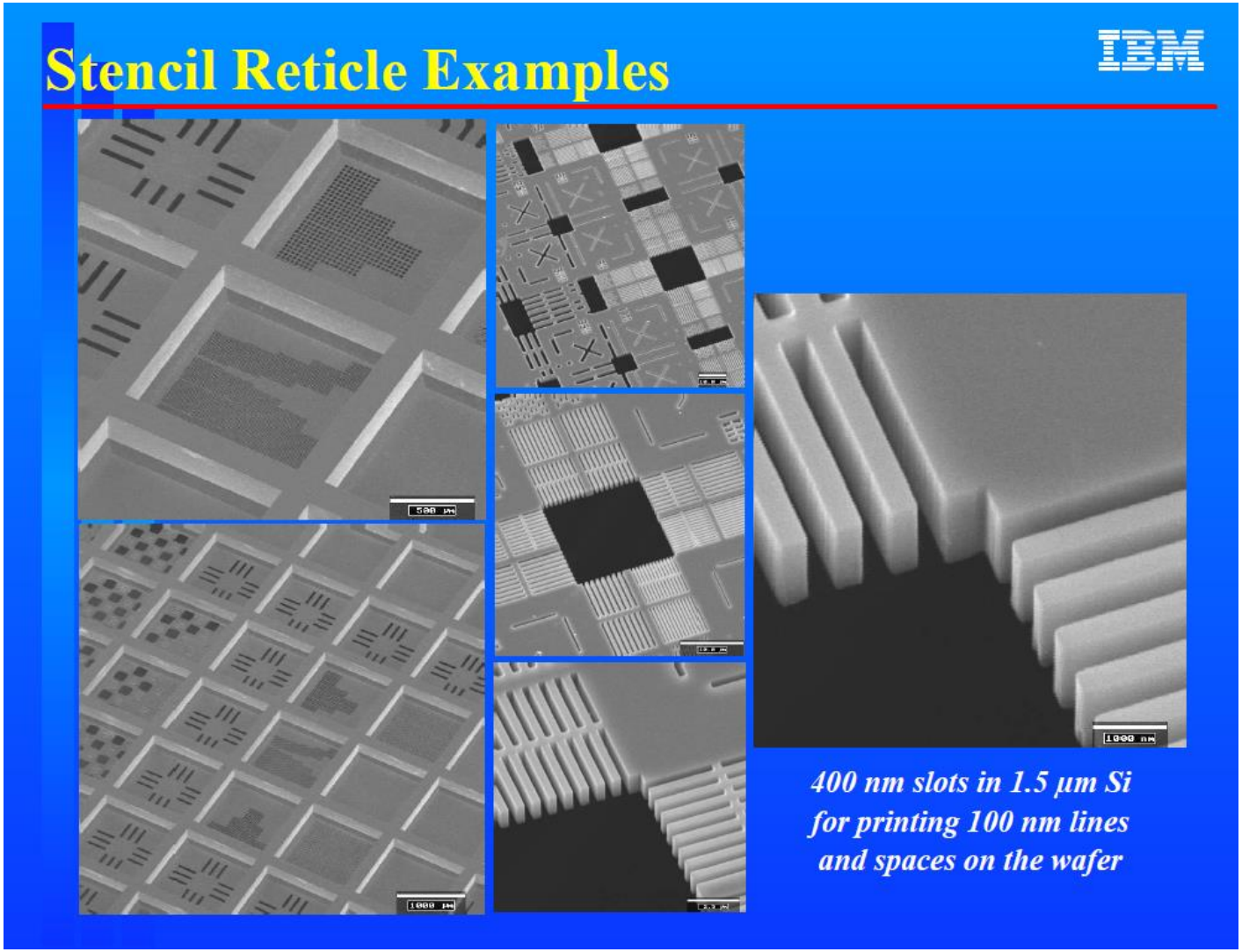
PREVAIL =
Variable Axis Immersion Lens with PRE-deflection

Division of projection area into subsections with optimum projection conditions

VAIL enables projection of far off-axis areas

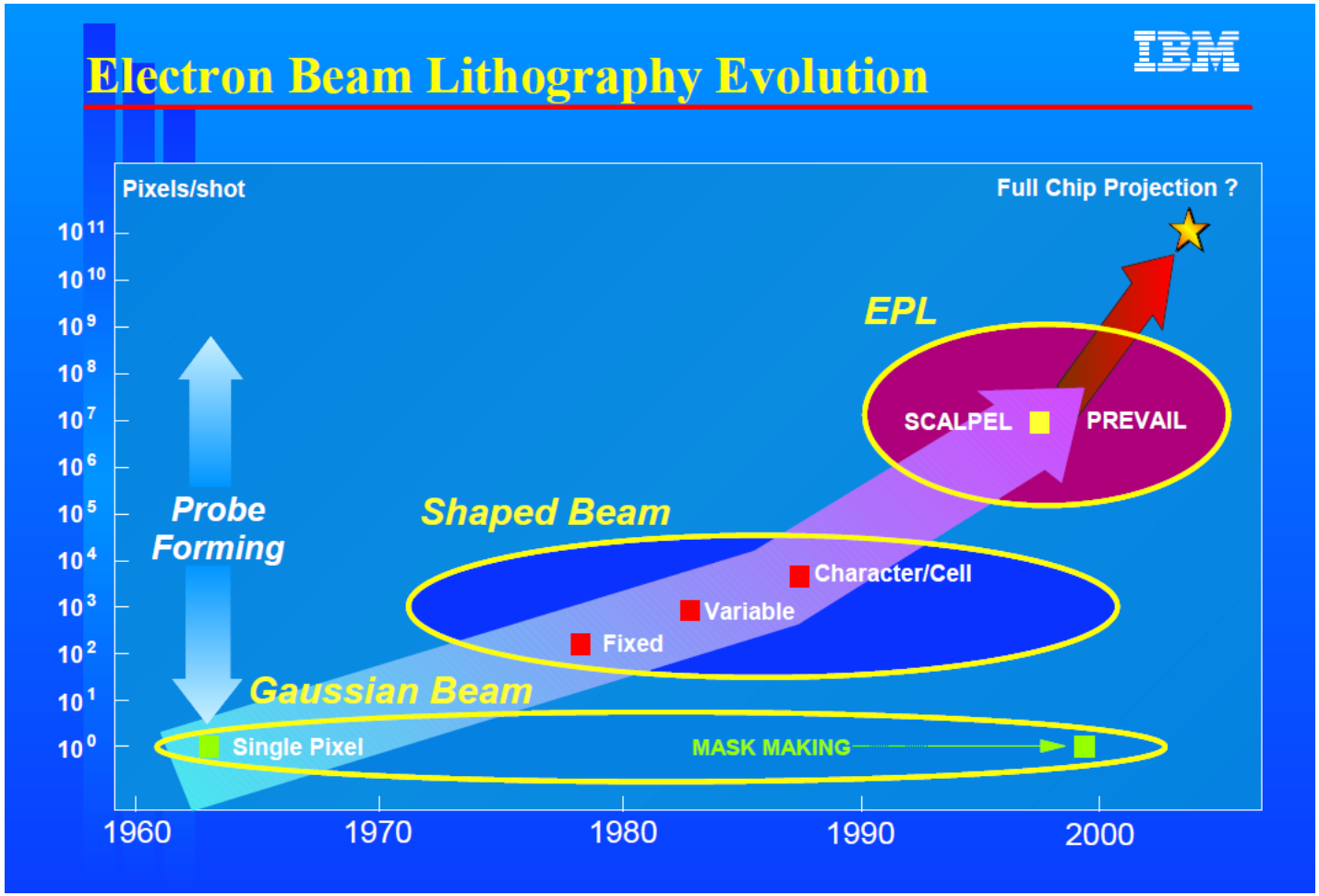
Courtesy H.C. Pfeiffer

Stencil-Reticle for PREVAIL



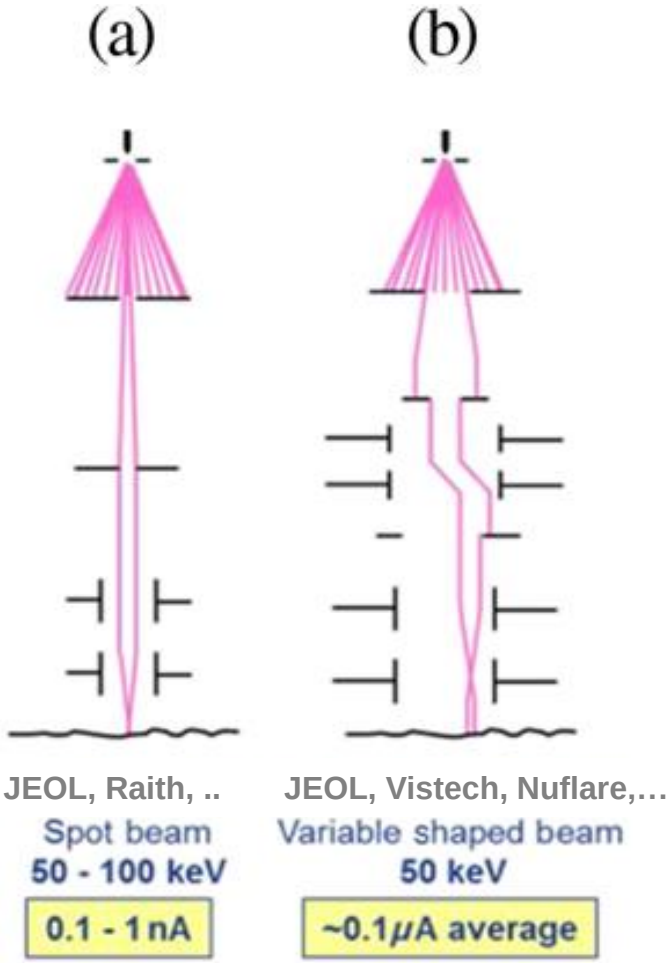
Courtesy H.C. Pfeiffer

E-beam evolution contiued



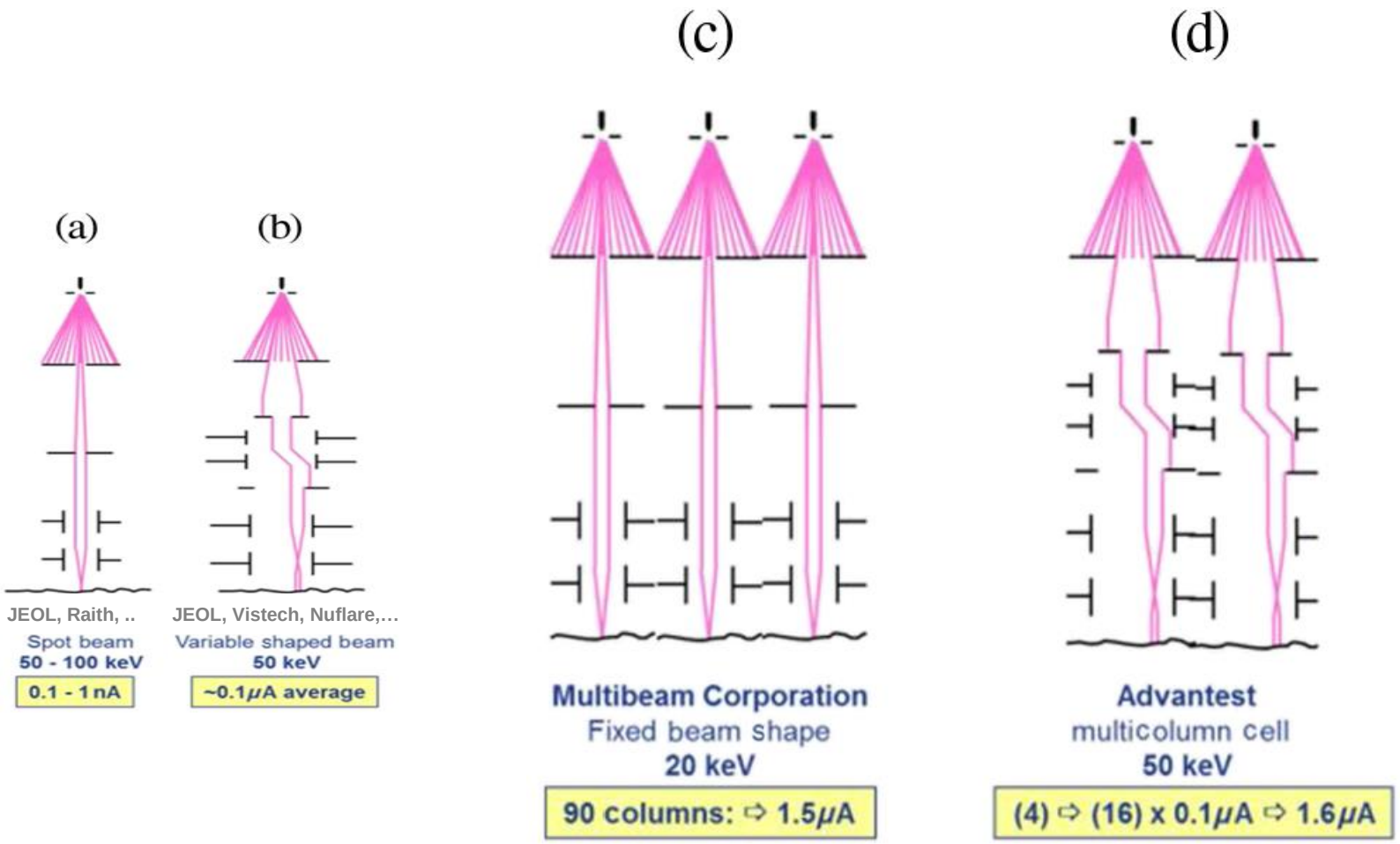
Courtesy H.C. Pfeiffer

E-beam evolution: single beam



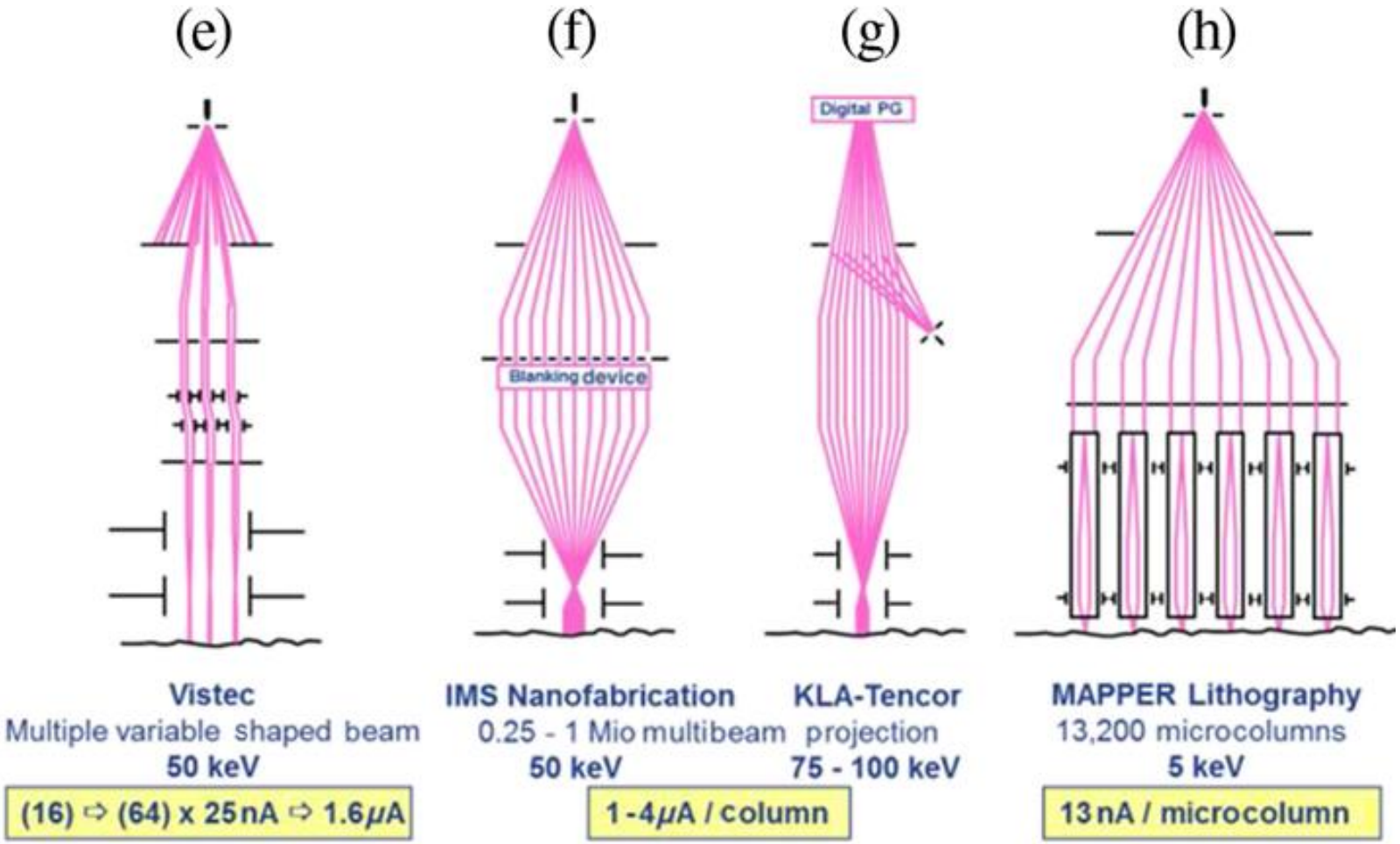
E. Platzgummer, C. Klein, H. Loeschner, J. Micro/Nanolith. MEMS MOEMS (2013)12, 031108

E-beam evolution: multiple columns



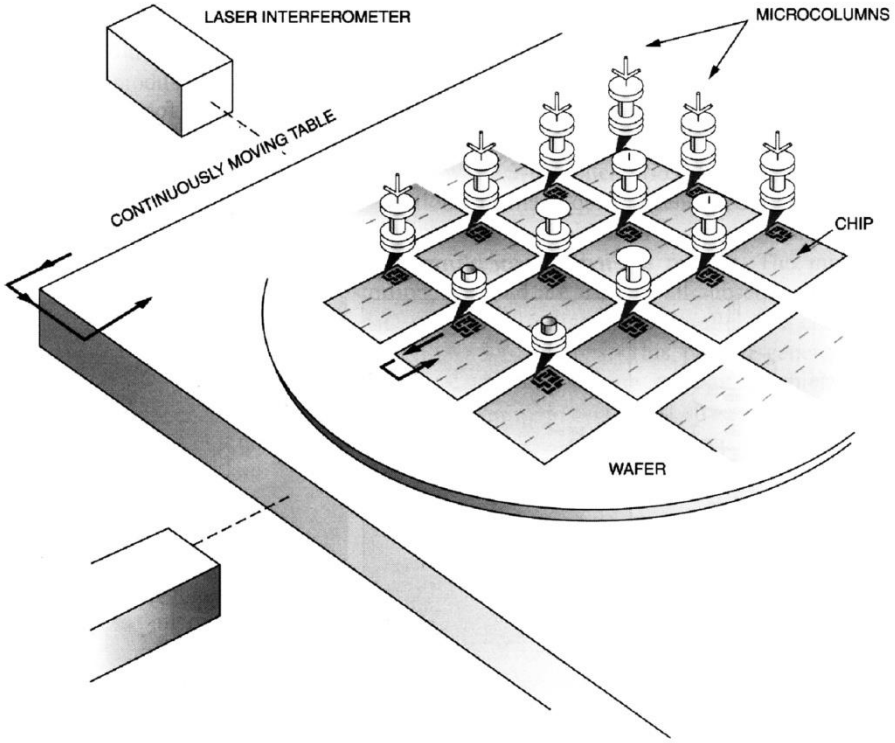
E. Platzgummer, C. Klein, H. Loeschner, J. Micro/Nanolith. MEMS MOEMS (2013)12, 031108

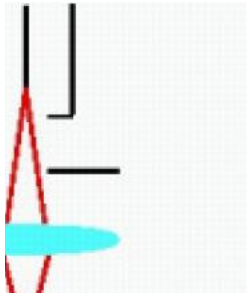
E-beam evolution: multibeams

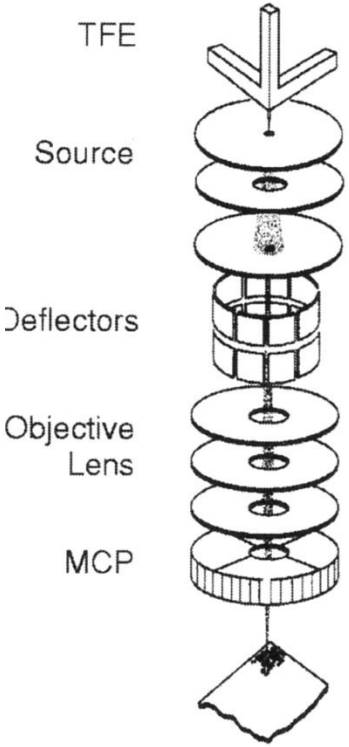


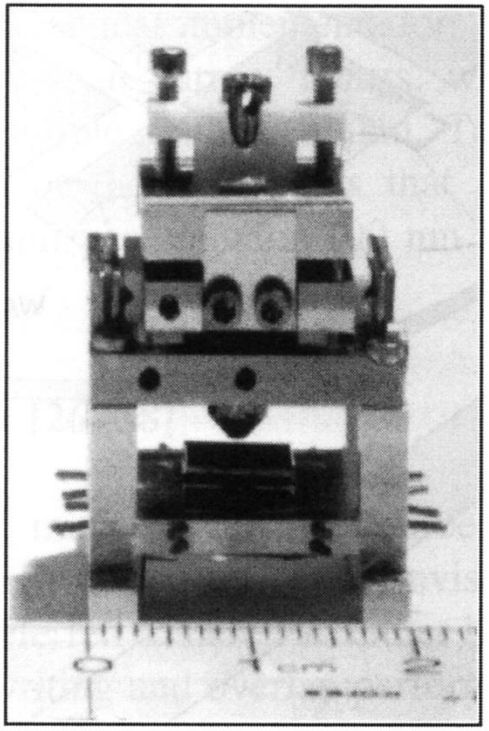
E. Platzgummer, C. Klein, H. Loeschner, J. Micro/Nanolith. MEMS MOEMS (2013)12, 031108

Multicolumn-concept









Concept of miniaturizitaion:
Arrays of miniaturized electron beam systems, “microcolumns”

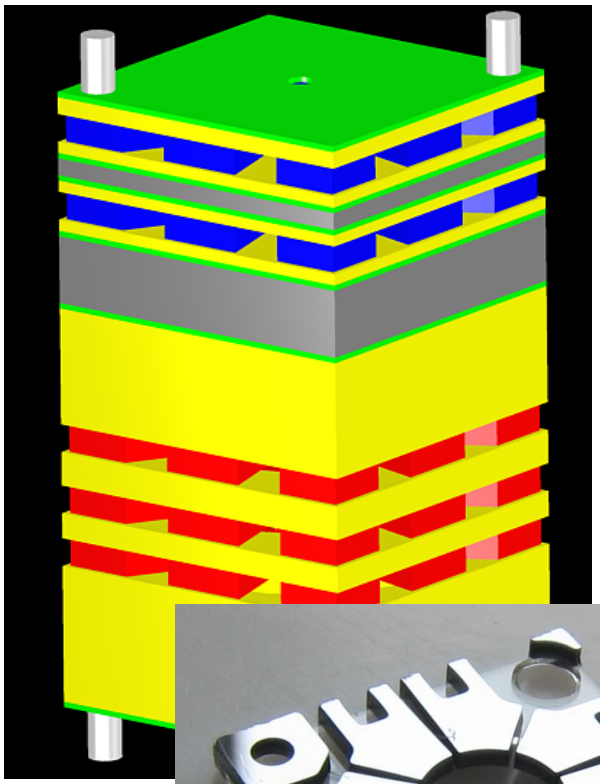
IBM / Etec

Electron optical scaling

Scaling of electron optical systems

	const. fields	const. potentials	selective*
Lengths	k	k	k or h
Potentials	k	1	1
Fields	1	$1/k$	$1/h$
Spherical aberration $d_S = \frac{1}{2}C_S\alpha^3$	k	k	k
Chromatic aberration $d_C = C_C\alpha\frac{\Delta V}{V}$	1	k	k
e-e interaction $d_e \propto (IL/V^2)^{\frac{2}{3}}$	$k^{-\frac{2}{3}}$	$k^{\frac{2}{3}}$	$h^{\frac{2}{3}}$
Effective source size: $d_{eff} = (d_o^2 + d_d^2 + d_S^2 + d_C^2 + d_e^2)^{\frac{1}{2}}$			
$d_{eff} \propto (C_S\lambda^3)^{\frac{1}{4}}$	$k^{-\frac{1}{8}}$	$k^{\frac{1}{4}}$	$k^{\frac{1}{4}}$
$d_{eff} \propto (C_C\lambda)^{\frac{1}{2}}$	$k^{-\frac{1}{4}}$	$k^{\frac{1}{2}}$	$k^{\frac{1}{2}}$
Effective brightness $\beta_{eff} = \frac{di}{df1}d_{eff}^{-2}$			
$\beta_{eff}(C_S\ ltd.)$	$k^{\frac{1}{4}}$	$k^{-\frac{1}{2}}$	$k^{-\frac{1}{2}}$
$\beta_{eff}(C_C\ ltd.)$	$k^{\frac{1}{2}}$	k^{-1}	k^{-1}

*k for critical retions, h for less critical regions



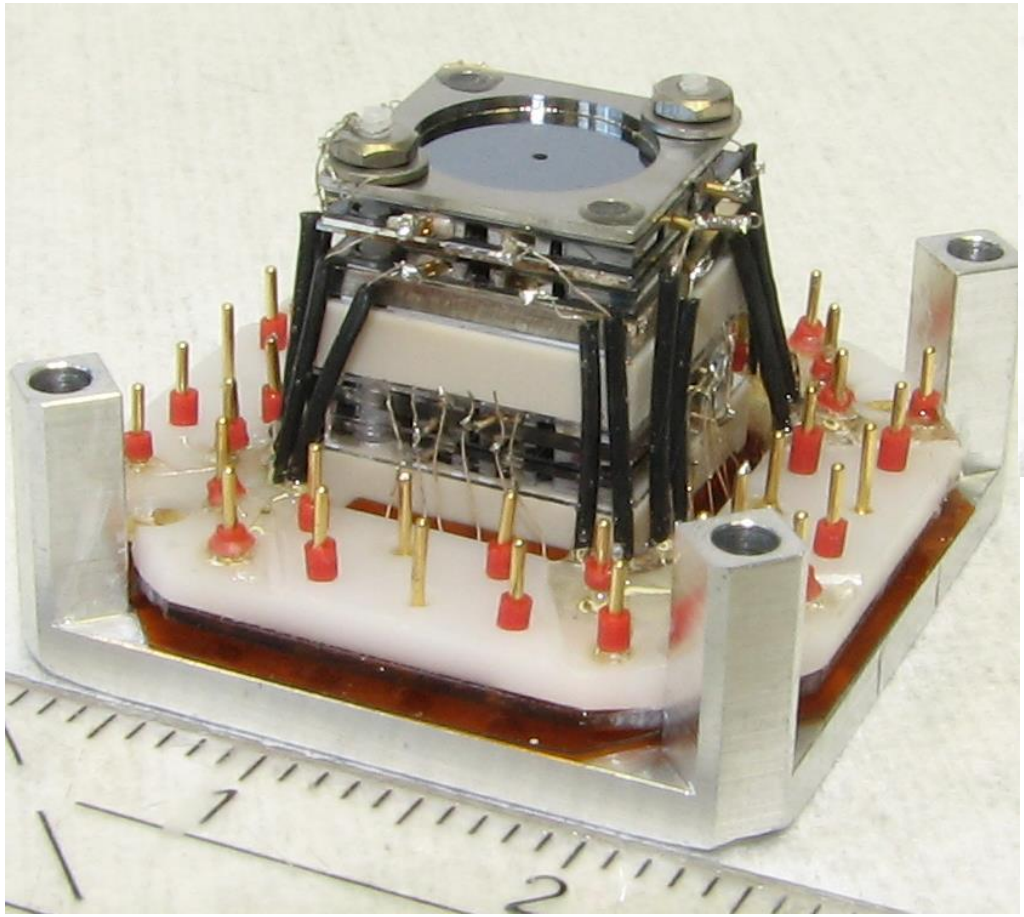
double deflector

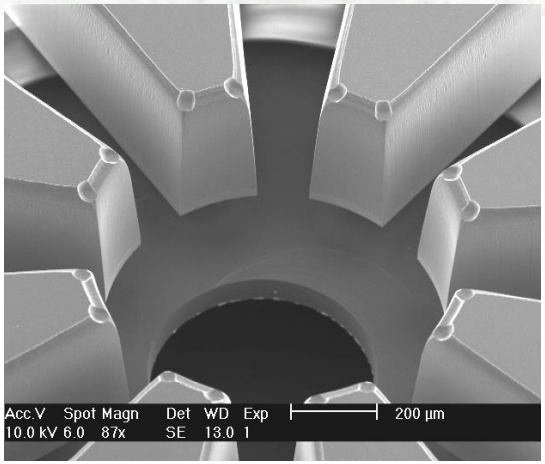
variable axis lens

H. Weigand et al. / Microelectronic Engineering 88 (2011) 2431–243, J. Vac. Sci.Technol. B27 (2009) 2542

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

Tübingen Microcolumn for wide-field application





Microcolumn with double deflector and Variable Axis Lens

1 gigapixel over 3x3 mm² area

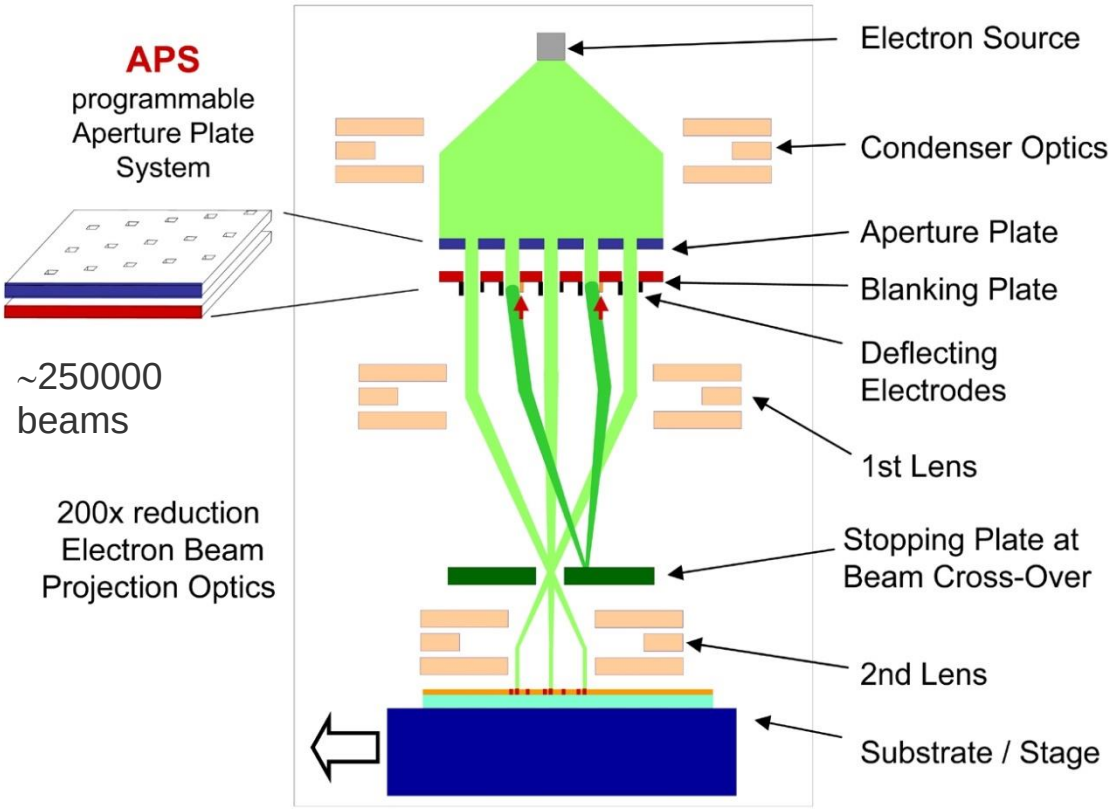
Octupole-elements, etched from Si-wafer

H. Weigand et al. / Microelectronic Engineering 88 (2011) 2431–243, J. Vac. Sci.Technol. B27 (2009) 2542

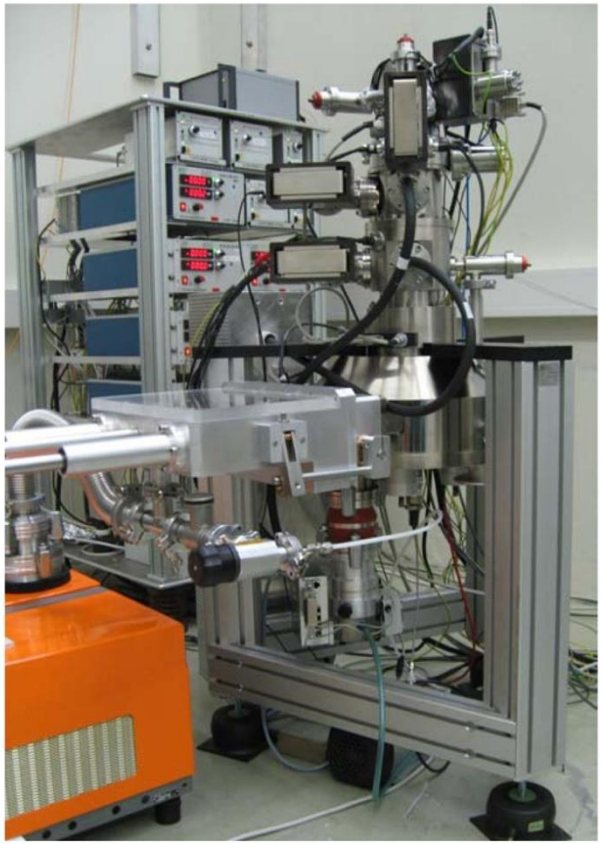
E-beam evolution: multi-beam approach

PML2 – Projection Mask-Less Lithography

IMS Nanofabrication

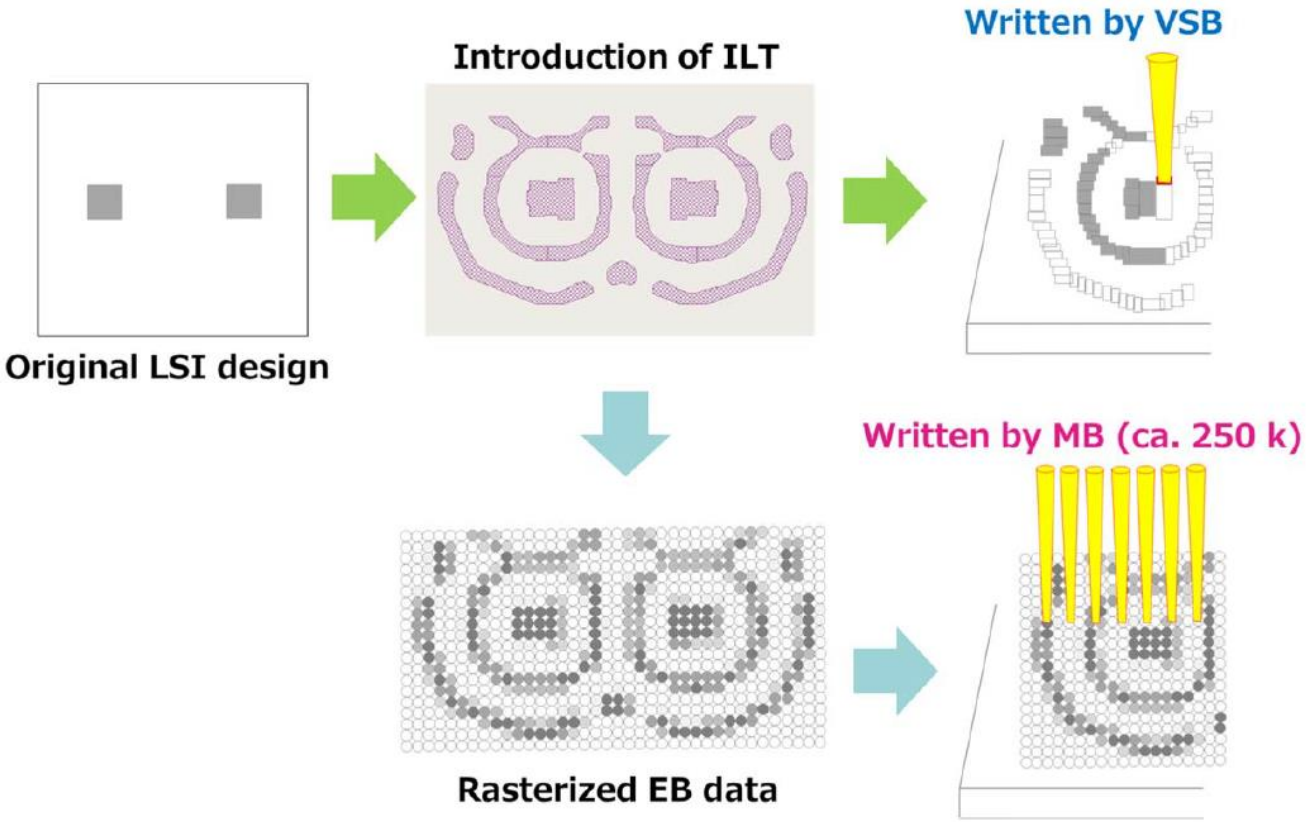


Rimana/Magic/… EU projects



PML2 proof-of-concept system

E-beam evolution: multi-beam approach



Patterning challenge from inverse lithography technology

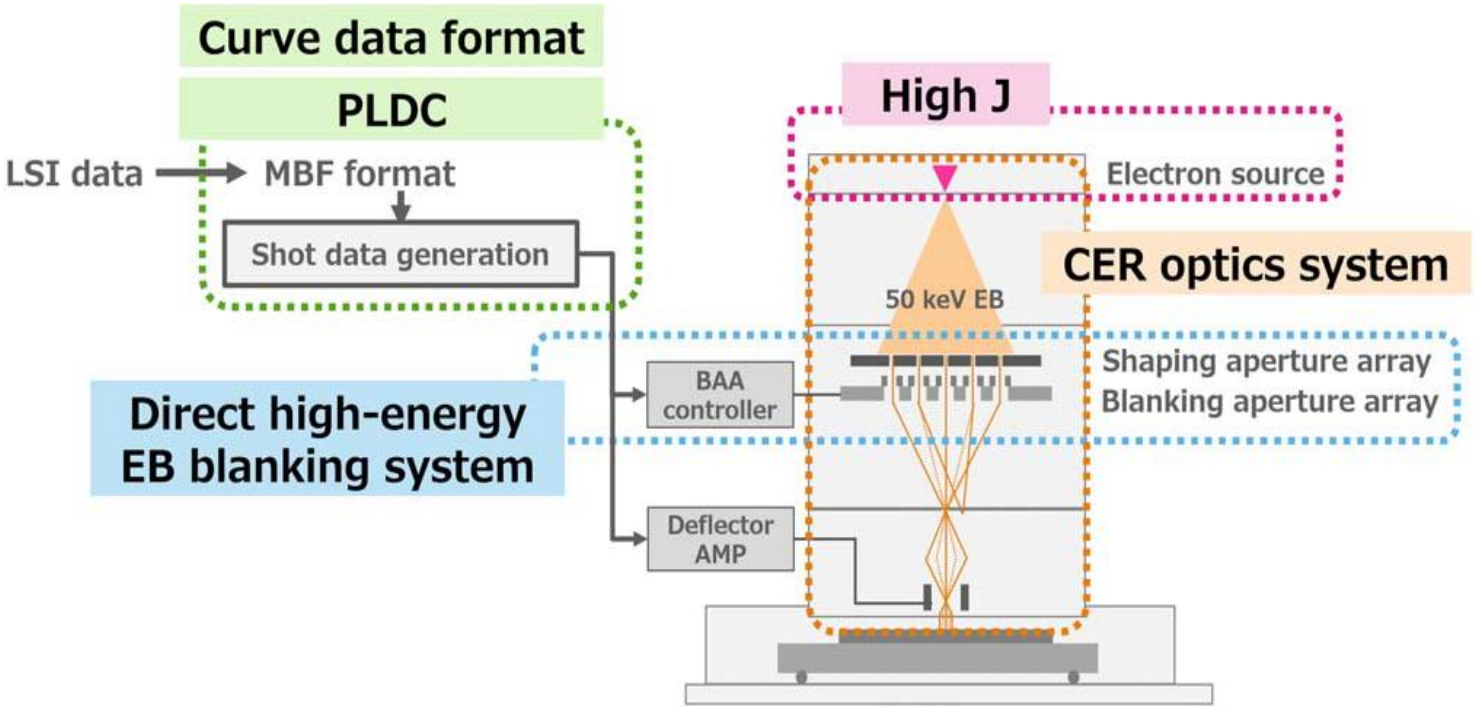
Multi-beam approach with pixel level dose correction well suited

J. Yasuda et al 2023 Jpn. J. Appl. Phys. 62 SG0803

E-beam evolution: multi-beam system

Key elements of a modern multi-beam system

e.g.: NuFlare MBM2000, IMS MBMW X01

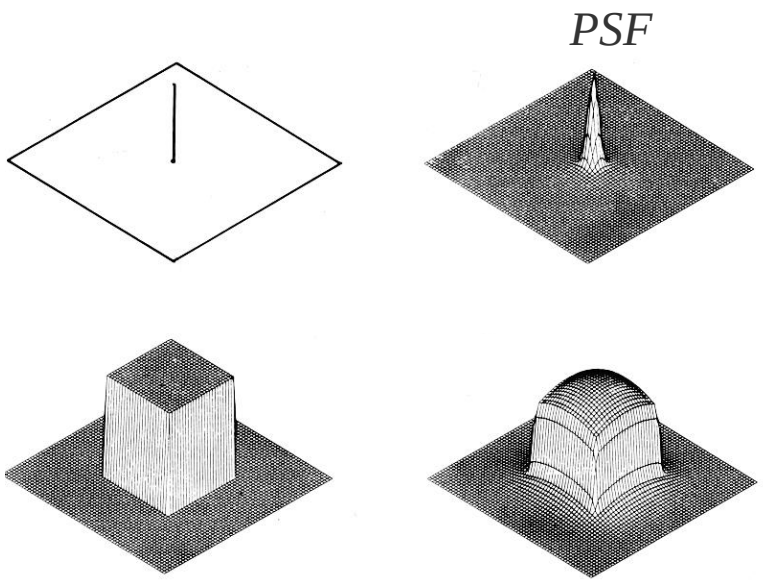


J. Yasuda et al. 2023 Jpn. J. Appl. Phys. 62 SG0803

Proximity effect

First comprehensive description: T.H.P. Chang, J. Vac. Sci. Technol. 12 (1975) 1271

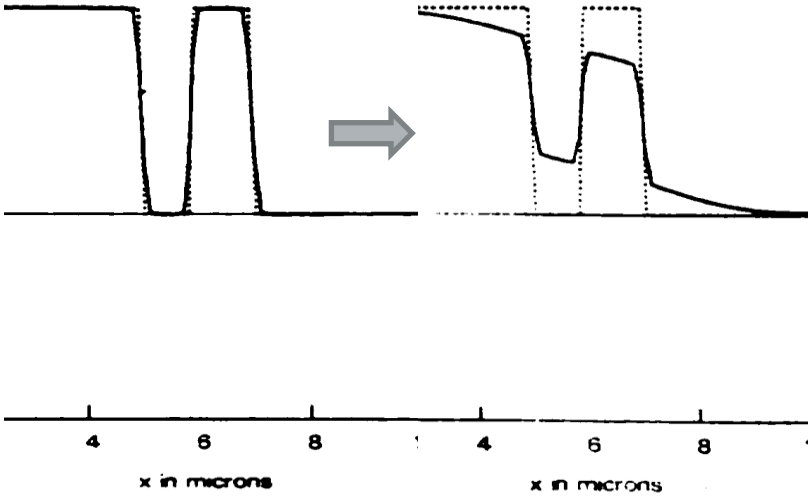
Finite point response, the point spread function (PSF), affected by electron optics, electron scattering in the resist and from the substrate, resist and process properties



Incident dose
D

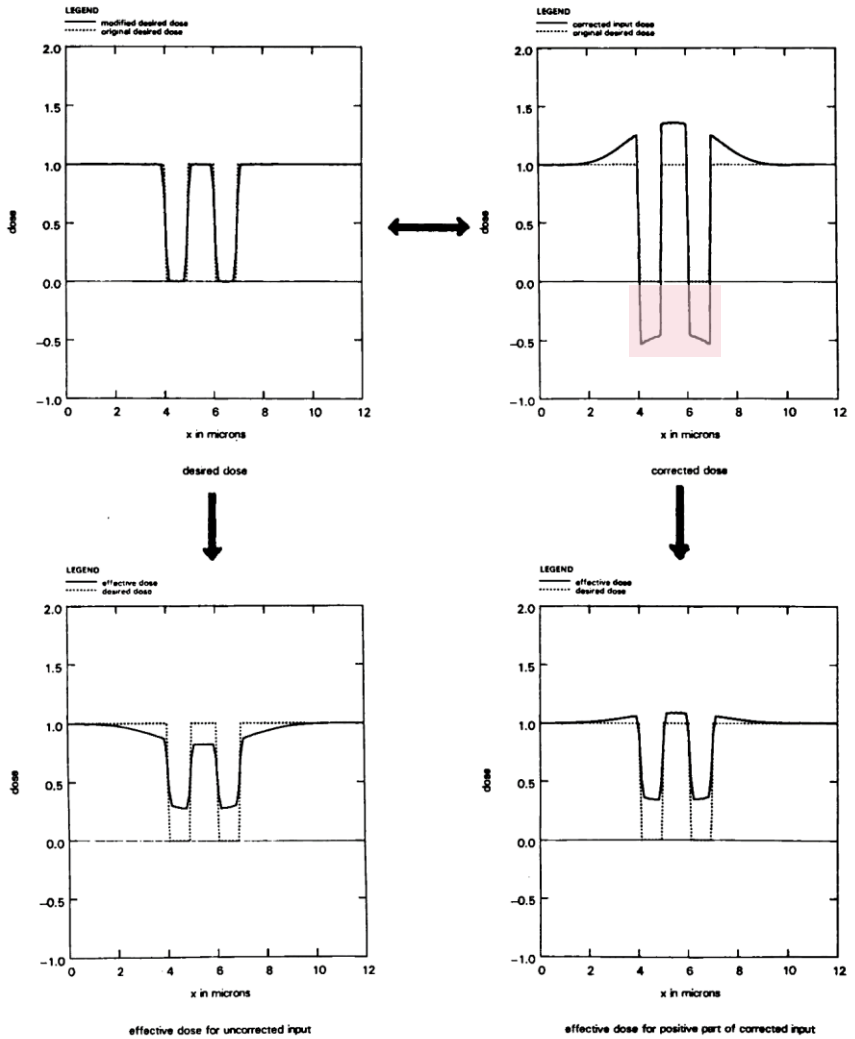
Deposited energy
E

$$e.g.\,PSF(r) = \frac{1}{\pi(1+\eta)}\left\{\frac{1}{\alpha^2}e^{-\frac{r^2}{\alpha^2}} + \frac{\eta}{\beta^2}e^{-\frac{r^2}{\beta^2}}\right\}$$



$$E(\vec{r}) = \int D(\vec{r}') \cdot PSF(\vec{r} - \vec{r}')dx'dy' = D * PSF$$

Proximity effect correction



FFT-inversion

non-physical result (negative doses) because desired pattern was non-physical

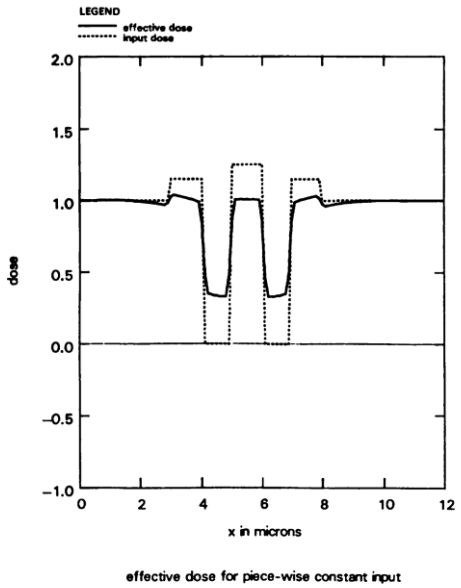
Shows two features for dose corrections:

dose variation between shapes required

higher doses near edges needed → shape partitioning

D.P. K., Proc. 9th Intern. Conf. on Electron and Ion Beam Science and Technology, R. Bakish Ed., Electrochemical Society, (1980) 80-6, 326-339

Proximity effect correction



effective dose for piece-wise constant input

Self-consistent proximity effect correction technique together with intelligent partitioning and zoning became very successful for Vector-Scan systems:
"All exposed shapes shall receive the same averaged deposited energy"

M. Parikh, J. Vac. Sci. Technol. 15 (1978) 931

Ghost: uncorrected exposure + exposure of free areas with defocused beam $(\sim\beta)$ and dose $\eta/(1+\eta)$ results in effective backscatter correction.

G. Owen, P. RissmanProximity effect correction for electron beam lithography by equalization of background doseJ. Appl. Phys. 54, 3573–3581 (1983)

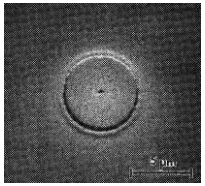
Since then many refinements in approach and implementation, see excellent review:

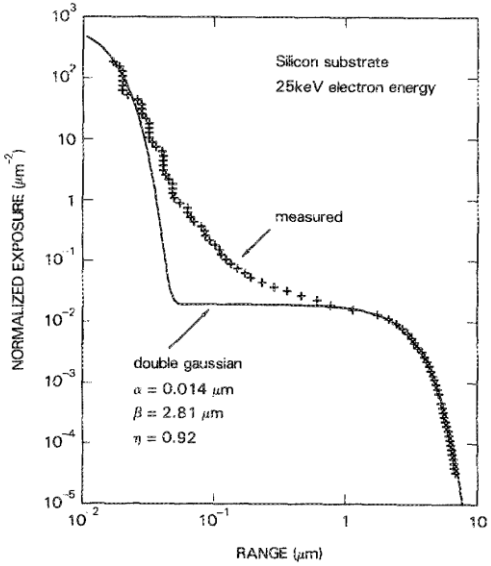
Ulrich Hofmann, Nezih Ünal, Jan Klikovits, From ghost to state-of-the-art process corrections – PEC enabled e-beam nanofabrication, MNE 25 (2024) 100286

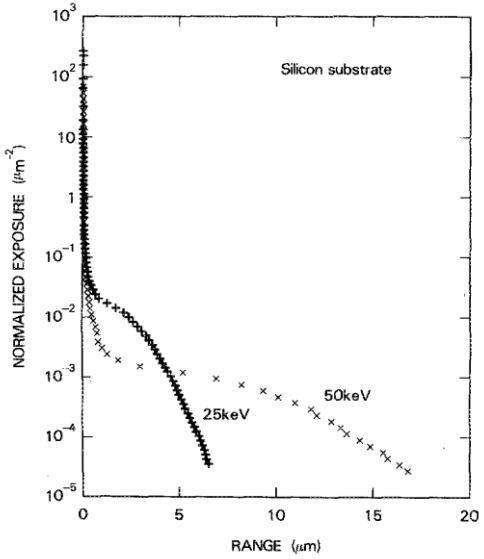
PSF for proximity effect correction

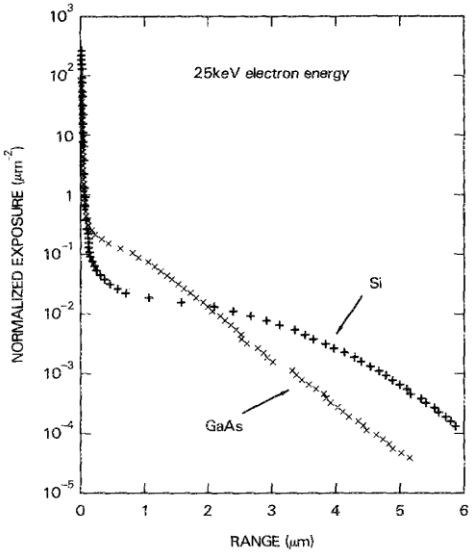
From Monte Caro simulations, ubiquitous

From experiment: measure radius r_i of the result of point exposures with charge Q_i over a large dose range (e.g. 7 orders of magnitude) → $PSF(r_i) = D_0/Q_i$, where D_0 is the large area (clearing for positive resist) dose.









S. A. Rishton and D. P. Kern, Point exposure distribution measurements, J. \lac. Sci. Technol. B5 (1987) 135

PSF for proximity effect correction

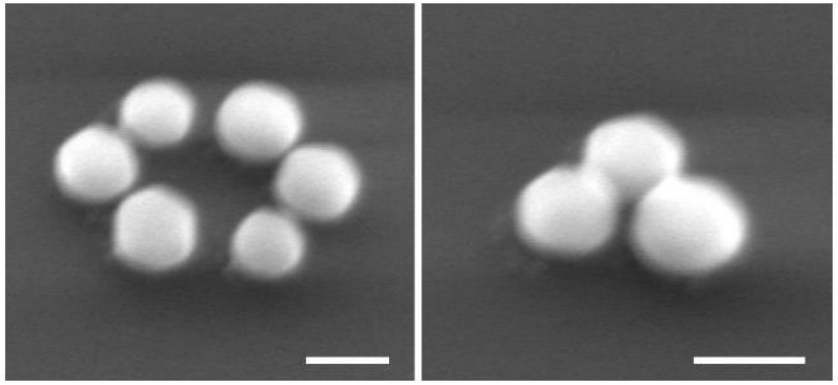
Substrate	Energy keV	approximation	α μm	β μm	η	γ μm	ν
Silicon	25	double Gaussian	0.014	2.81	0.92	-	-
Silicon	50	double Gaussian	0.033	8.80	0.75	-	-
10μm AZ on Si	25	double Gaussian	0.020	5.22	0.35	-	-
GaAs	25	double Gaussian	0.017	1.21	3.24	-	-
GaAs	25	Gaussian + exponential	0.014	-	-	0.57	2.52
GaAs	50	double Gaussian	0.013	3.28	1.07	-	-
GaAs	50	double Gaussian + exponential	0.013	3.78	0.75	1.28	0.54

PSF model:

$$PSF(r) = \frac{1}{\pi(1+\eta+\gamma)}\left\{\frac{1}{\alpha^2}e^{-\frac{r^2}{\alpha^2}} + \frac{\eta}{\beta^2}e^{-\frac{r^2}{\beta^2}} + \frac{\nu}{2\gamma^2}e^{-\frac{r}{\gamma}}\right\}$$

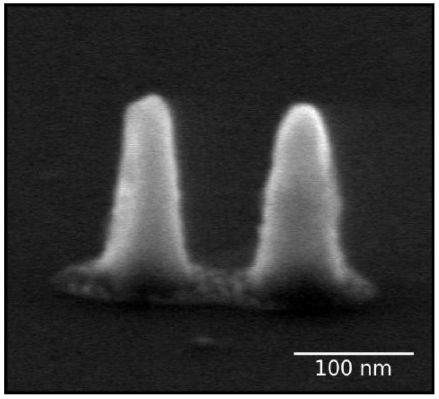
S. A. Rishton and D. P. Kern, Point exposure distribution measurements, J. \lac. Sci. Technol. B5 (1987) 135

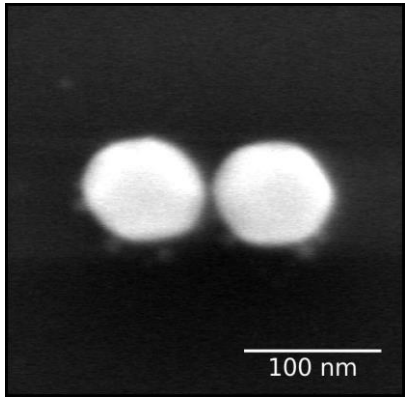
Make the best out our your machine/process



Goal: fabricate sub-100nm gold sphere oligomeres with defined separation

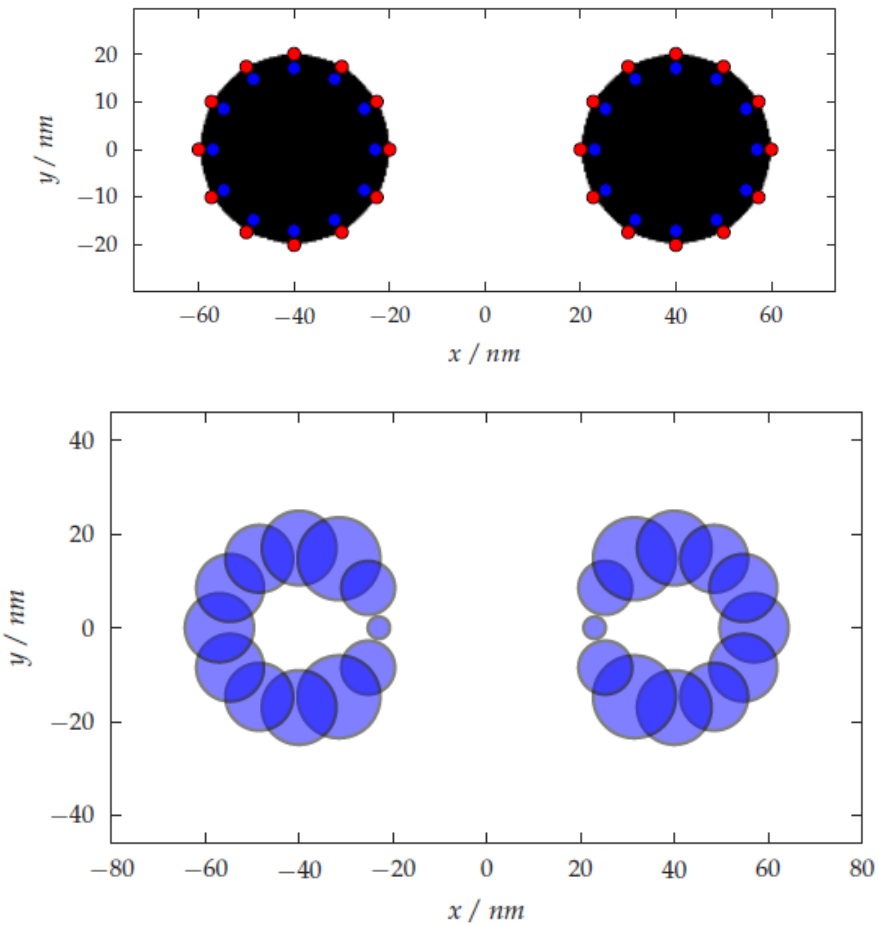
approach: fabricate closely spaced Au pillars and melt them. The size of the spheres is determined by the volume of the pillars.





Simon Dickreuter, Herstellung von Oligomeren aus Nano-Kugeln und deren Charakterisierung, PhD thesis, University of Tübingen (2019)

Make the best out our your machine/process



Exposure strategy in SEM with XENOS pattern generator:

Expose red dots,
determine their doses such that all the blue points receive the same exposure

The sizes of the blue circles are proportional to the dose for the corresponding dot exposures.

pixel level dose correction and pattern adapted exposure strategy

Simon Dickreuter, Herstellung von Oligomeren aus Nano-Kugeln und deren Charakterisierung, PhD thesis, University of Tübingen (2019)

Conclusion

Electron beam lithography was initiated by the quest to miniaturize electronics and to fabricate nanoscopic structures for basic research

Starting from SEM-type electron optical systems dedicated machines with advanced electron optics, digital control, laser based metrology were developed through the 1970s and 80s, and still going on, used for R&D.

Various ways to increase throughput were pursued since at least till the advent of EUV-lithography E-beam direct write lithography was considered the only way to reach the dimensions projected in the semiconductor roadmap.

Maskmaking for semiconductor technology, versatile fabrication for research and technology implementation on the nanometer level in electronics, photonics, phononics,…. appears to be today's function of EBL.

Acknowledgments

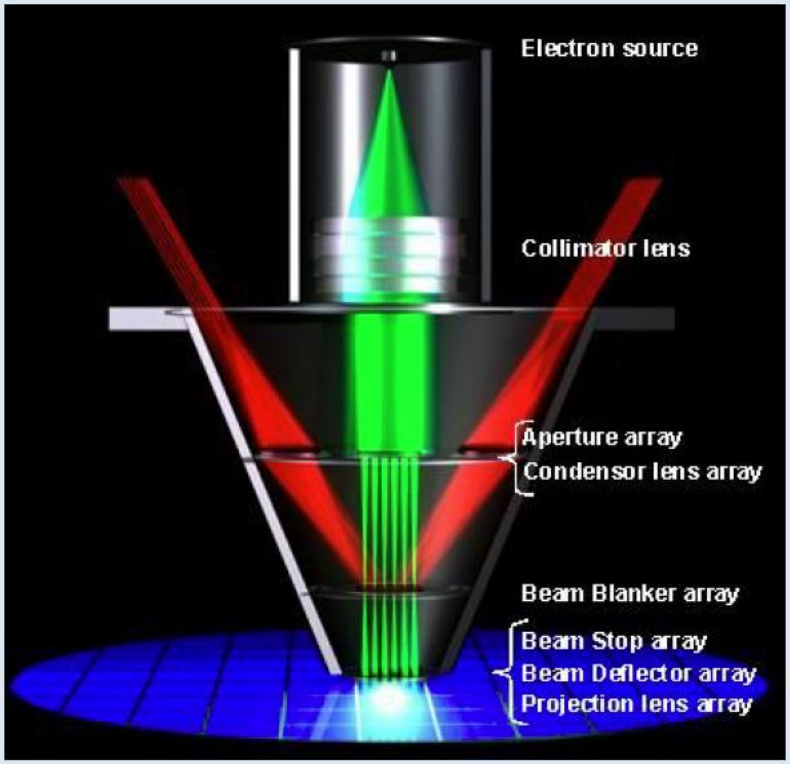
Thanks go to many former and present colleagues:

- Gottfried Möllenstedt for sparking very early interest
- Alec Broers, Philip Chang, Mike Hatzakis, Steve Rishton, George Sai-Halasz, Matt Wordemann, …. at IBM for continued encouragement and wonderful device work
- Janos Kirz, David Attwood, Erik Anderson for the exciting x-ray optics work
- and the members of my (former) group in Tübingen, in particular Helmut Weigand, and now Monika Fleischer with her nano-plasmonics group, here in particular Simon Dickreuter

Thank you for your attention!

Multibeam-Ansatz

MAPPER builds a system with 13,000 parallel electron beams for 10 wph

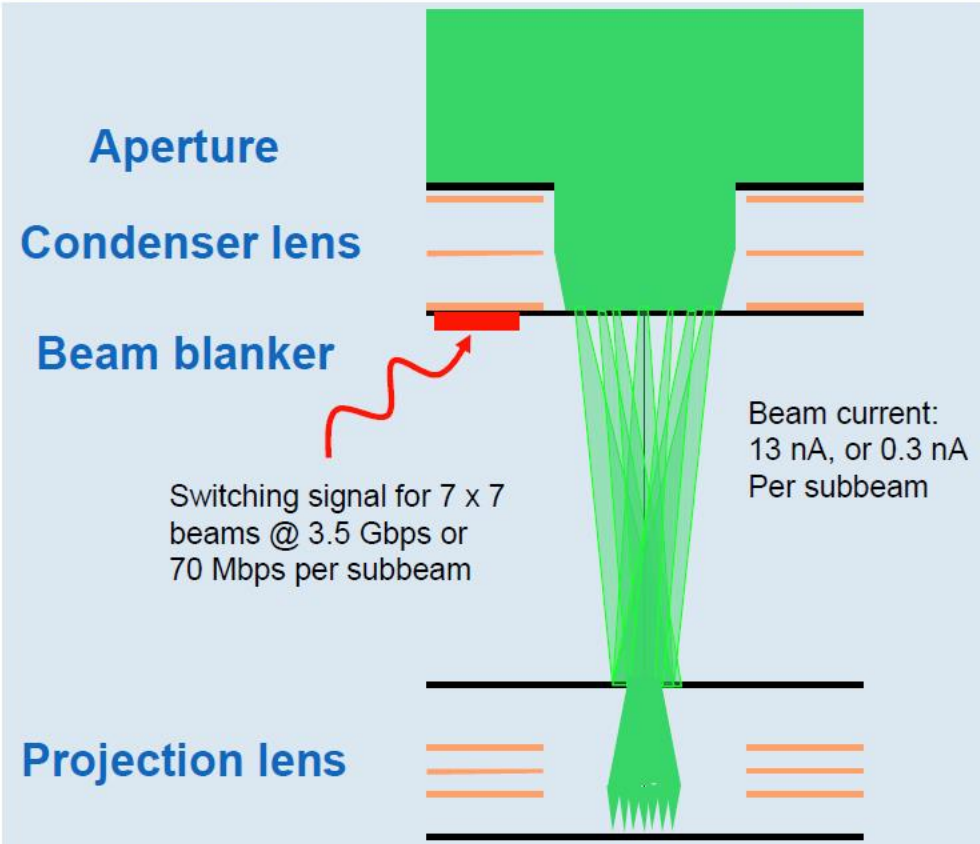


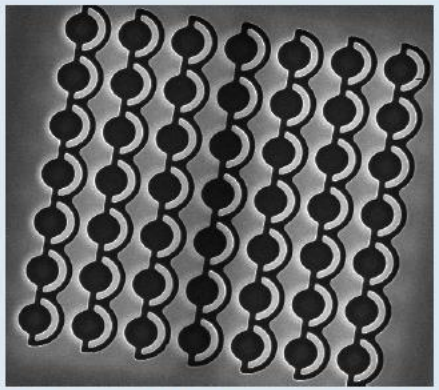
Key numbers 22nm node:

	HVM	pre-alpha
#beams and data channels	13,000	110
Spotsize:	25 nm	35 nm
Beam current:	13 nA	0.3 nA
Datarate/channel	70 MHz	20 MHz
Acceleration voltage	5 kV	5 kV
Nominal dose	30 $\mu C/cm^2$	30 $\mu C/cm^2$
Throughput @ nominal dose	10 wph	0.002 wph
Pixel size @ nominal dose	3.5nm	2.25 nm
Wafer movement	Scanning	Static

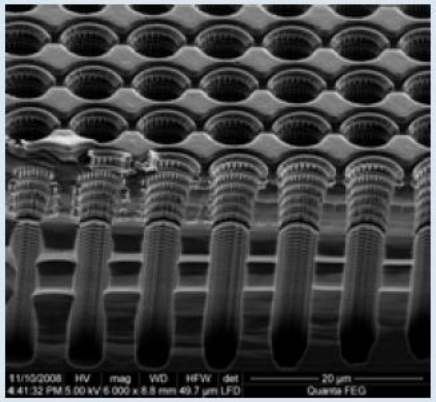
Multibeam-Ansatz

High beam current is achieved through ‘patterned beam’ approach





Top view of (7 x 7) blanking deflectors



Cross section of (7 x 7) blanking deflectors