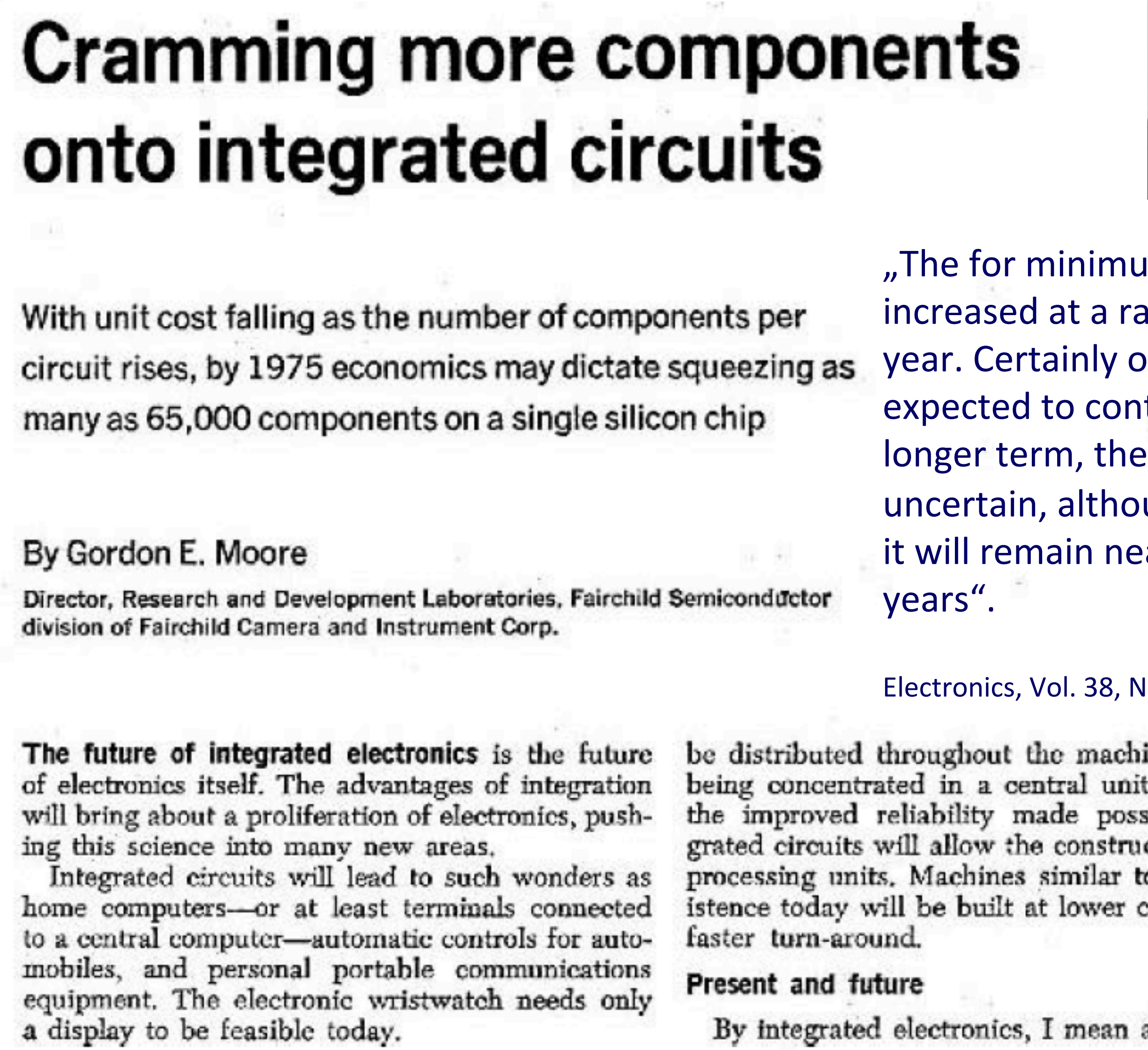
Lithographie

Moore's Law


(INTEL)



Cramming more components onto integrated circuits

With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore

Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

The future of integrated electronics is the future of electronics itself. The advantages of integration will bring about a proliferation of electronics, pushing this science into many new areas.

Integrated circuits will lead to such wonders as home computers—or at least terminals connected to a central computer—automatic controls for automobiles, and personal portable communications equipment. The electronic wristwatch needs only a display to be feasible today.

be distributed throughout the machine instead of being concentrated in a central unit. In addition, the improved reliability made possible by integrated circuits will allow the construction of larger processing units. Machines similar to those in existence today will be built at lower costs and with faster turn-around.

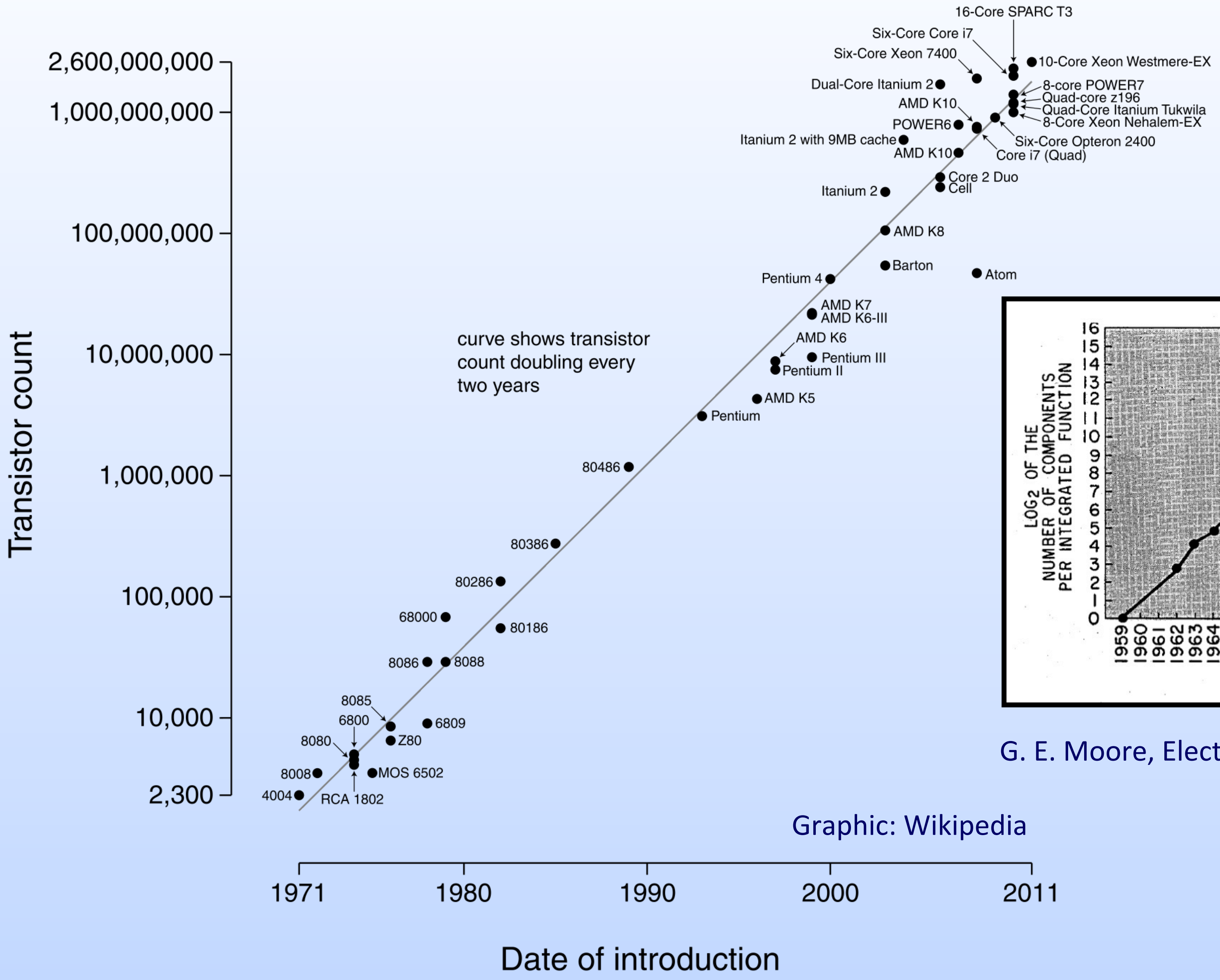
Present and future

By integrated electronics, I mean all the various

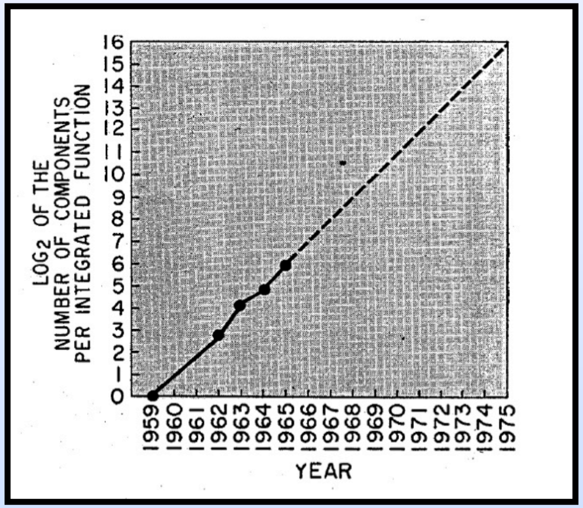
„The for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short this rate can be expected to continue, if not increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will remain nearly constant for at least 10 years".

Electronics, Vol. 38, Nb. 8, April 19, 1965, pp. 114-117.

Moore's Law



Graphic: Wikipedia



G. E. Moore, Electronics, 1965.

Prozesse der Photolithographie

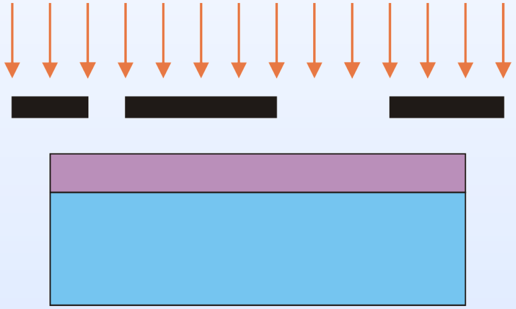
Resistauftrag

- Spin Coating
- Feuchtigkeit: ±0.5%
- Temperatur: ±0.2°C
- Lackdickeuniformität (Wafer): < 0.3 nm
- Softbake 90-100°C

Wafer Prime (HMDS):
- besserer Adhäsion

Belichtung

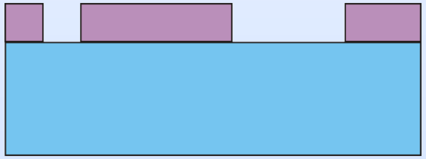
Ausheizen nach der Beleuchtung (verringert mechanische Spannungen)



Entwicklung

(Tank, Spray, Puddle)

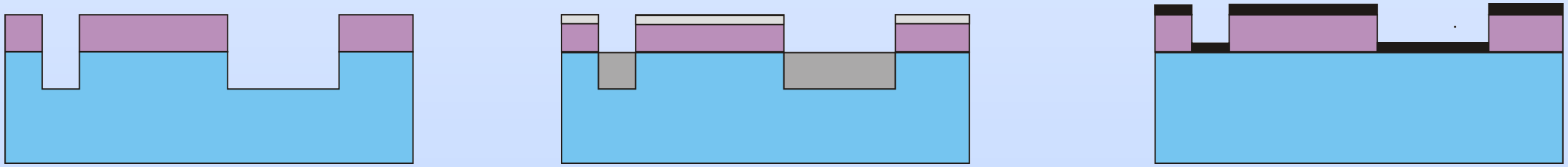
Postbake
- verbesserte Adhäsion
- zus. Stabilität gegen Ätzprozesse



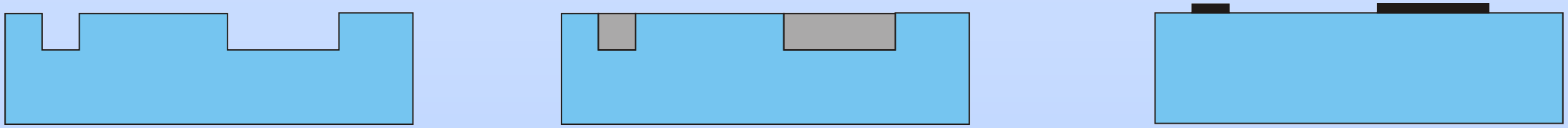
Ätzen

Dotieren

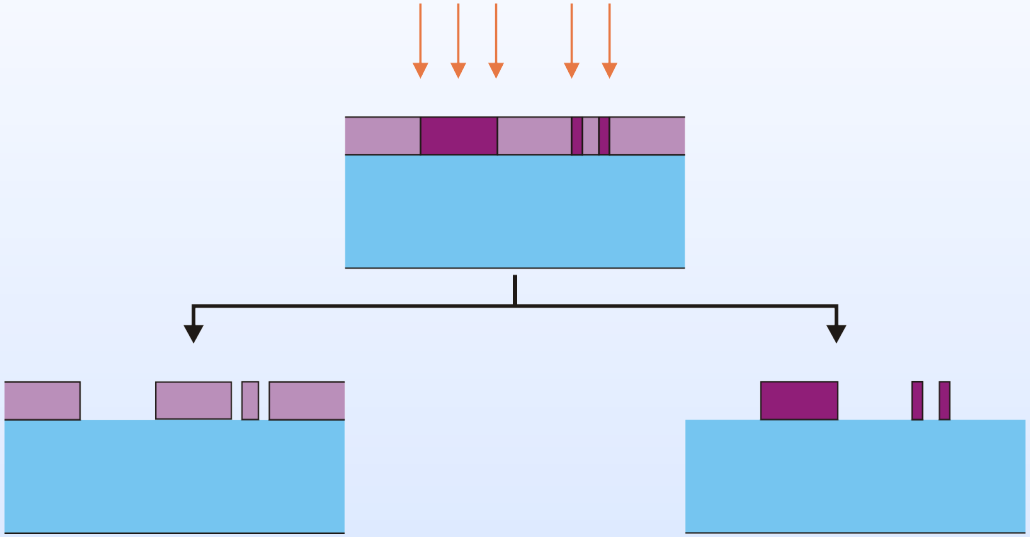
Schichtabscheiden



Resist entfernen (Resiststripping)



Resist



Positiv-Resist

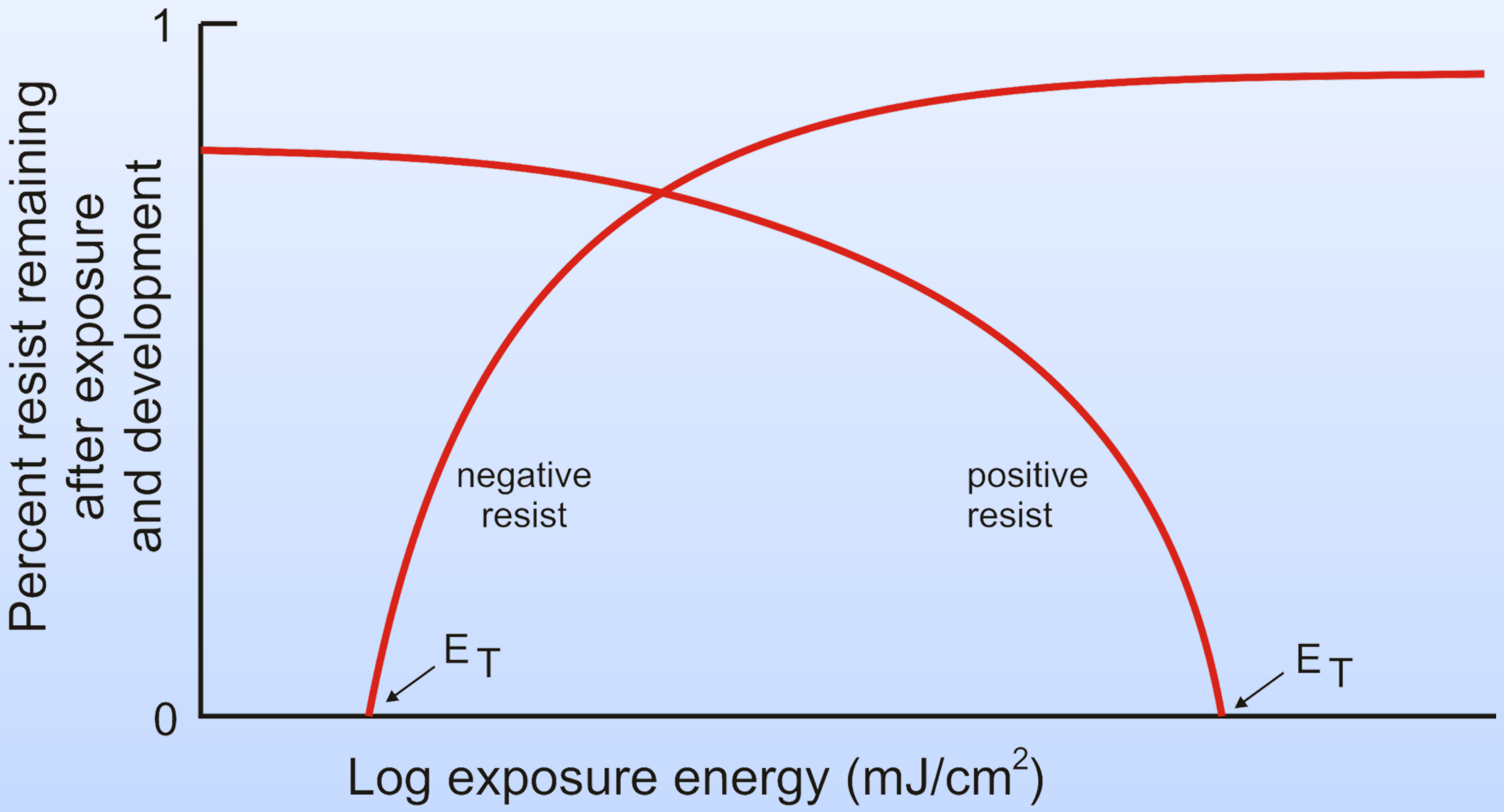
- Wolff Umwandlung
  (hydrophob zu hydrophil)
- Bestrahlung verursacht Kettenbrüche (PMMA)
  => Bessere Löslichkeit

Negativ-Resist

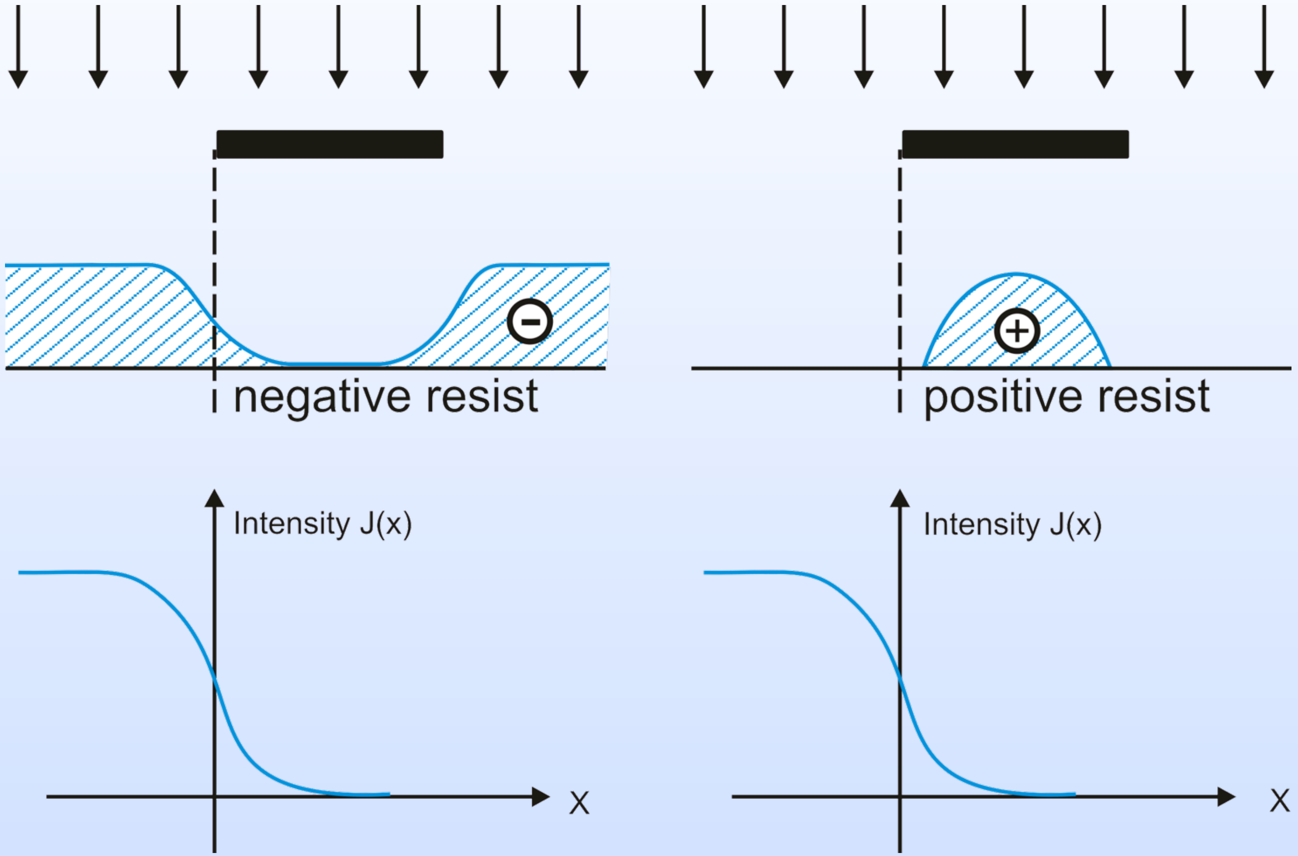
- Vernetzung Reaktion

Belichtungscharakteristik

- Belichtungszeit ist abhängig von der Schwellenenergie E_T
- Kontrast resultiert aus der Flankensteilheit
- Dunkelabtrag



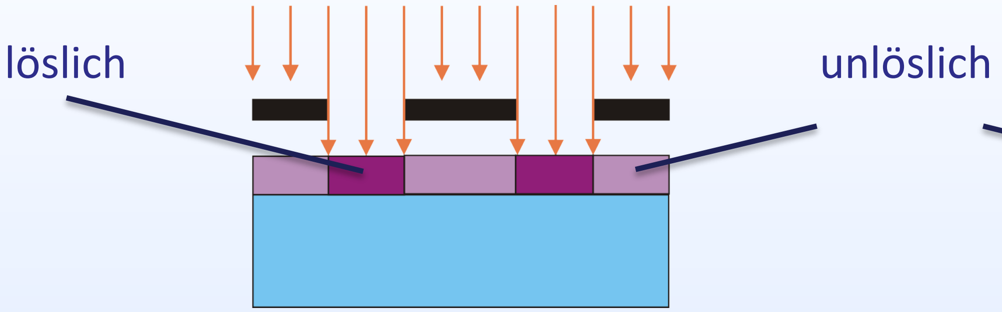
Lackprofile nach Entwicklung



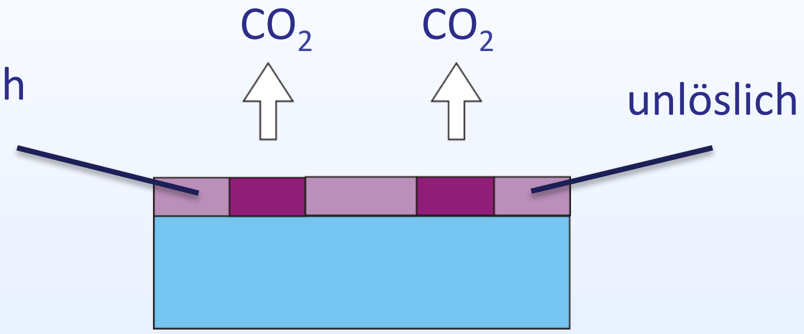
Die belichteten und entwickelten Resisprofile weichen sich durch Kantenverrundung vom Rechteckprofil ab, aufgrund:

- Intensitätsverteilung in abgeschatteten Bereichen
- Kontrast und Dunkelabtrag des Resist

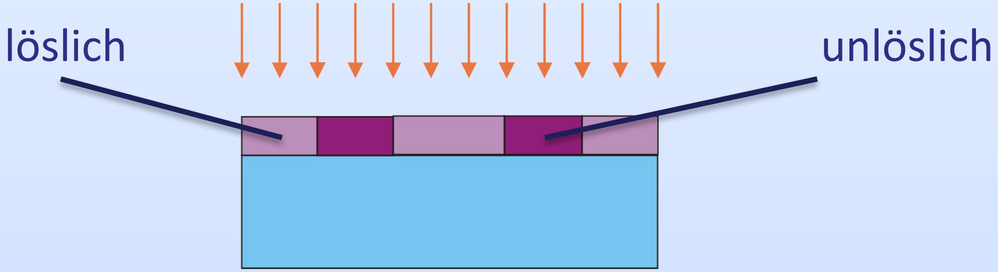
Image Reversal im Positiv-Resist



1. Belichtung durch Maske



2. Bake (ca. 90°C)

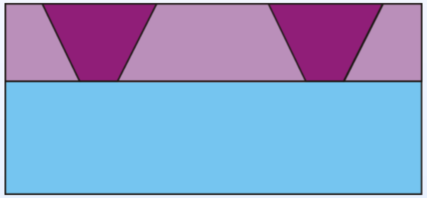


3. Fluchtbelichtung

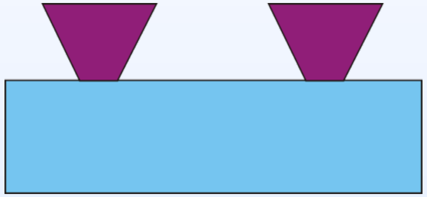
4. Entwickeln

- Resist wird zwei mal belichtet und zwischen Belichtungen chemisch modifiziert
  → positiv-Resist verhält sich wie hochaufgelösender Negativ-Resist

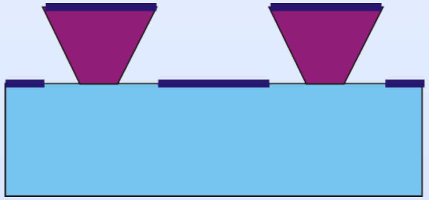
Image Reversal: Umkehr des Kantenprofils, Lift-Off



1. Belichtung



2. Image Reversal



3. Beschichtung

4. Resiststripping

Lift-Off: Strukturierung von Metallen ohne Ätzung

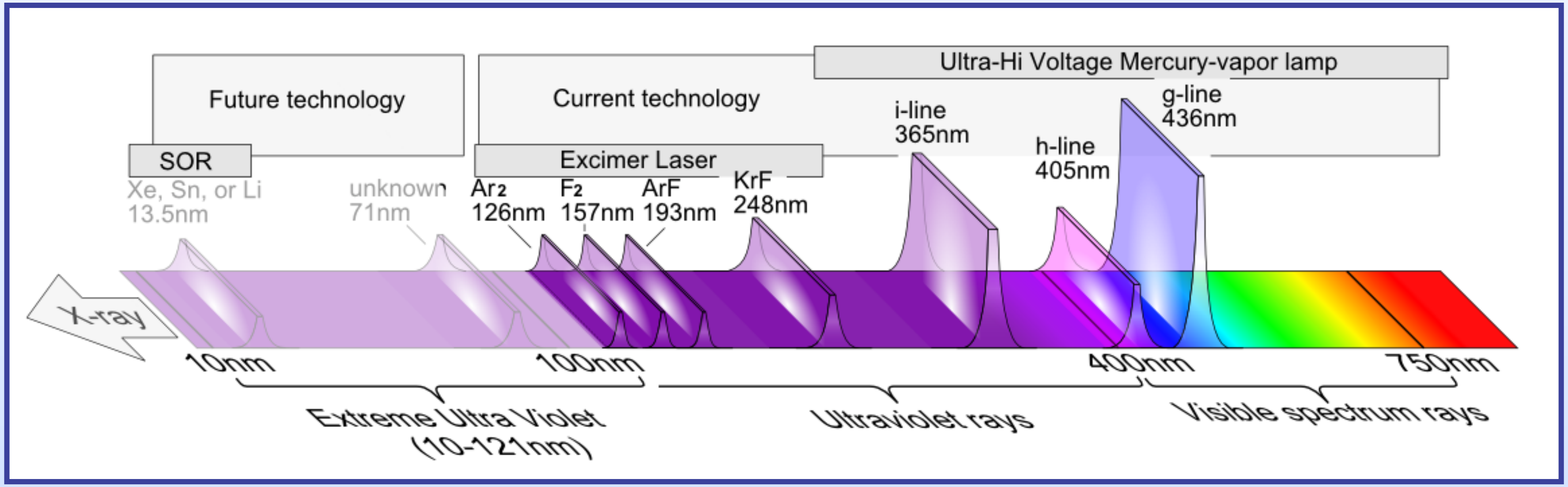
- Strukturierung von Photoresists
- Ganzflächige Metallabscheidung
- Ablösen des Photoresists (Metall auf Photoresist wird entfernt, Metall auf Substrat bleibt)

Vergleich Positiv- / Negativ-Resist

	Positiv-Resist	Negativ-Resist
Minimale Strukturbreite	< 0.5 µm	Ca. 2 µm
Aspektverhältnis	gut	mässig
Lift-Off	möglich	nicht möglich
Thermische Stabilität	gut (bis 200°C)	mässig
Staubpartikel	kaum Einfluss	bewirken Löcher
Passivierung bei Plasma-Ätzung	sehr gut	mässig
Passivierung bei Nasschemie	mässig	sehr gut
Kosten	teurer	günstiger

Lichtquellen

- Optische Lithographie (Standardverfahren)
- Röntgenlithographie (X-Ray Lithography)

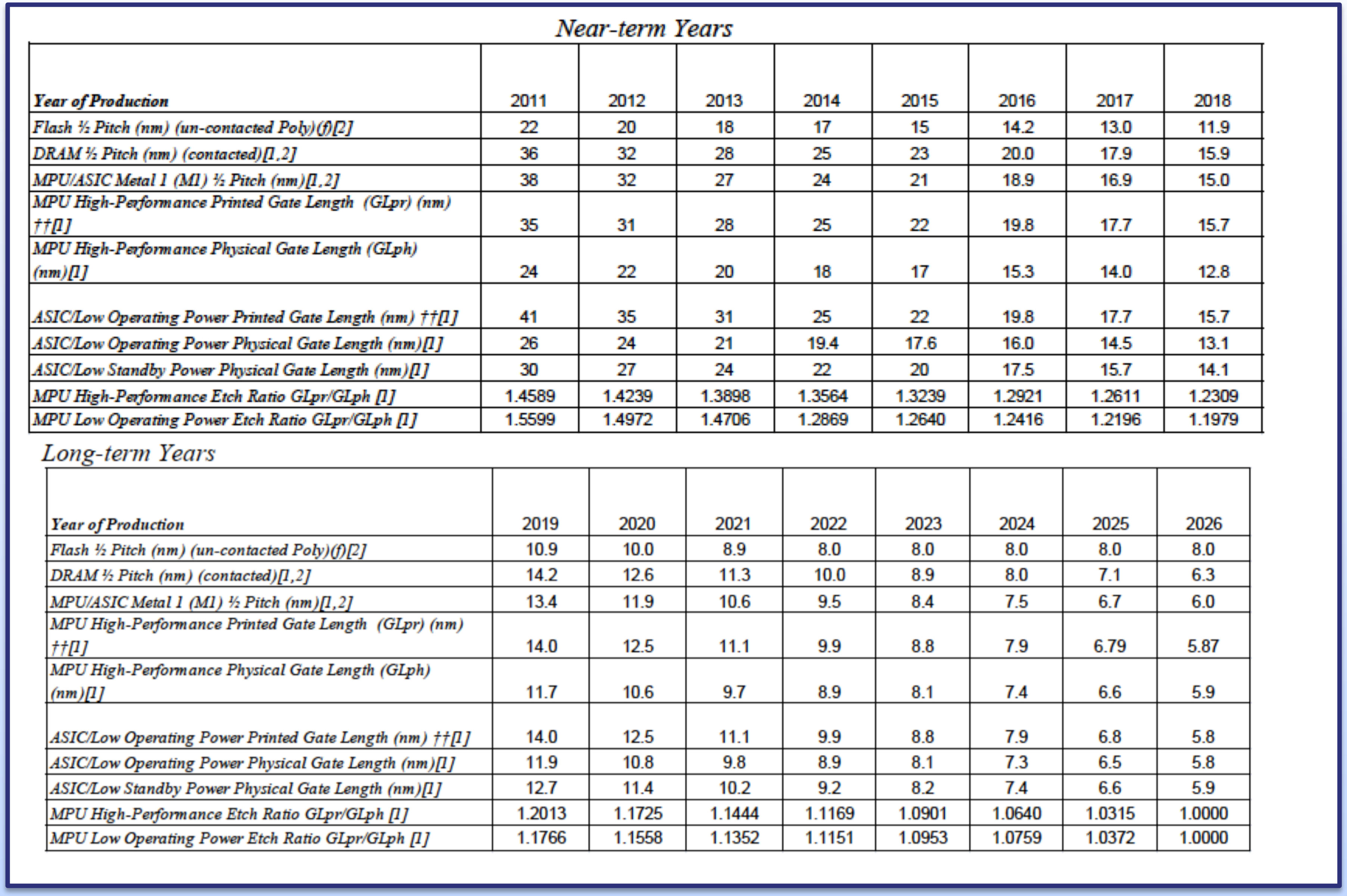


- Elektronenstrahl Lithographie
- Ionenstrahl Lithographie

De Broglie Wellenlänge

$$\lambda = \frac{h}{mV}$$

International Technology Roadmap for Semiconductors



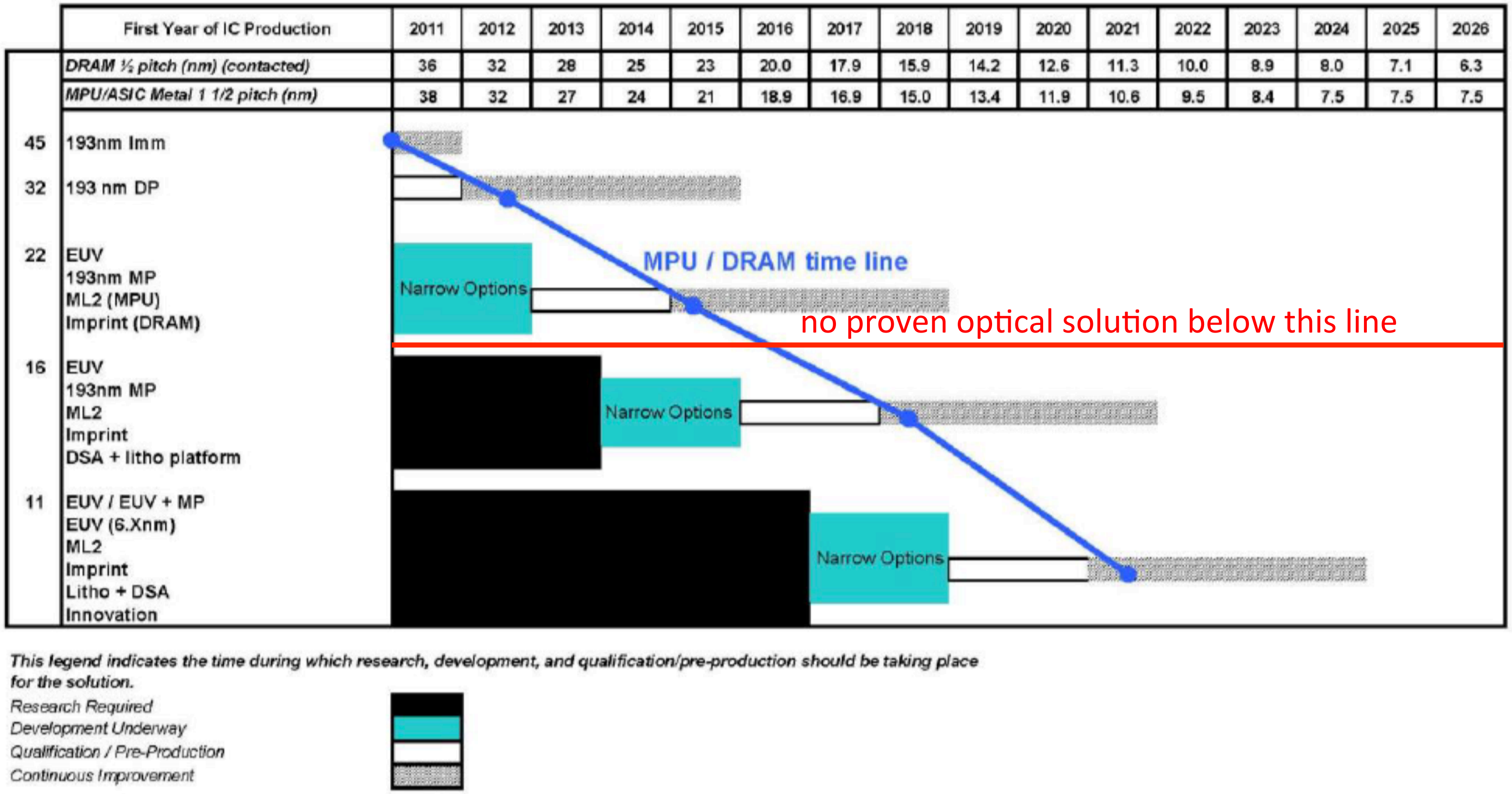
Near-term Years

Year of Production	2011	2012	2013	2014	2015	2016	2017	2018
Flash ½ Pitch (nm) (un-contacted Poly)(f)[2]	22	20	18	17	15	14.2	13.0	11.9
DRAM ½ Pitch (nm) (contacted)[1,2]	36	32	28	25	23	20.0	17.9	15.9
MPU/ASIC Metal 1 (M1) ½ Pitch (nm)[1,2]	38	32	27	24	21	18.9	16.9	15.0
MPU High-Performance Printed Gate Length (GLpr) (nm) ††[1]	35	31	28	25	22	19.8	17.7	15.7
MPU High-Performance Physical Gate Length (GLph) (nm)[1]	24	22	20	18	17	15.3	14.0	12.8
ASIC/Low Operating Power Printed Gate Length (nm) ††[1]	41	35	31	25	22	19.8	17.7	15.7
ASIC/Low Operating Power Physical Gate Length (nm)[1]	26	24	21	19.4	17.6	16.0	14.5	13.1
ASIC/Low Standby Power Physical Gate Length (nm)[1]	30	27	24	22	20	17.5	15.7	14.1
MPU High-Performance Etch Ratio GLpr/GLph [1]	1.4589	1.4239	1.3898	1.3564	1.3239	1.2921	1.2611	1.2309
MPU Low Operating Power Etch Ratio GLpr/GLph [1]	1.5599	1.4972	1.4706	1.2869	1.2640	1.2416	1.2196	1.1979

Long-term Years

Year of Production	2019	2020	2021	2022	2023	2024	2025	2026
Flash ½ Pitch (nm) (un-contacted Poly)(f)[2]	10.9	10.0	8.9	8.0	8.0	8.0	8.0	8.0
DRAM ½ Pitch (nm) (contacted)[1,2]	14.2	12.6	11.3	10.0	8.9	8.0	7.1	6.3
MPU/ASIC Metal 1 (M1) ½ Pitch (nm)[1,2]	13.4	11.9	10.6	9.5	8.4	7.5	6.7	6.0
MPU High-Performance Printed Gate Length (GLpr) (nm) ††[1]	14.0	12.5	11.1	9.9	8.8	7.9	6.79	5.87
MPU High-Performance Physical Gate Length (GLph) (nm)[1]	11.7	10.6	9.7	8.9	8.1	7.4	6.6	5.9
ASIC/Low Operating Power Printed Gate Length (nm) ††[1]	14.0	12.5	11.1	9.9	8.8	7.9	6.8	5.8
ASIC/Low Operating Power Physical Gate Length (nm)[1]	11.9	10.8	9.8	8.9	8.1	7.3	6.5	5.8
ASIC/Low Standby Power Physical Gate Length (nm)[1]	12.7	11.4	10.2	9.2	8.2	7.4	6.6	5.9
MPU High-Performance Etch Ratio GLpr/GLph [1]	1.2013	1.1725	1.1444	1.1169	1.0901	1.0640	1.0315	1.0000
MPU Low Operating Power Etch Ratio GLpr/GLph [1]	1.1766	1.1558	1.1352	1.1151	1.0953	1.0759	1.0372	1.0000

Lithography roadmap



First Year of IC Production	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
DRAM ½ pitch (nm) (contacted)	36	32	28	25	23	20.0	17.9	15.9	14.2	12.6	11.3	10.0	8.9	8.0	7.1	6.3
MPU/ASIC Metal 1 1/2 pitch (nm)	38	32	27	24	21	18.9	16.9	15.0	13.4	11.9	10.6	9.5	8.4	7.5	7.5	7.5

45	193nm Imm
32	193 nm DP
22	EUV 193nm MP ML2 (MPU) Imprint (DRAM)
16	EUV 193nm MP ML2 Imprint DSA + litho platform
11	EUV / EUV + MP EUV (6.Xnm) ML2 Imprint Litho + DSA Innovation

This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

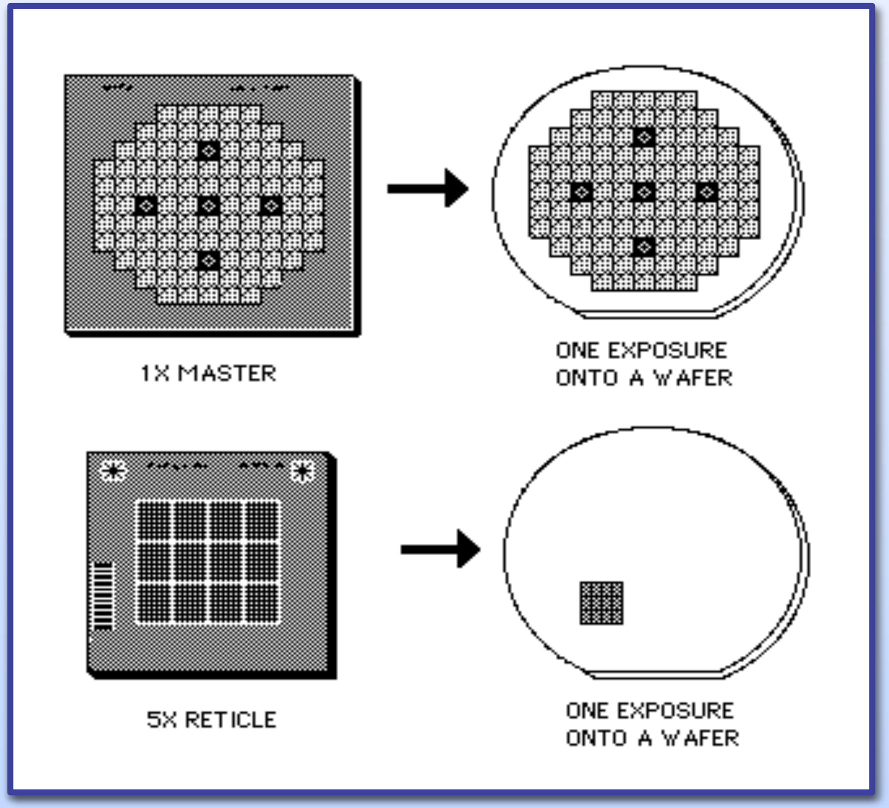
Research Required ■
Development Underway 🟦
Qualification / Pre-Production ☐
Continuous Improvement ▨

Source: International Technology Roadmap for Semiconductors 2011

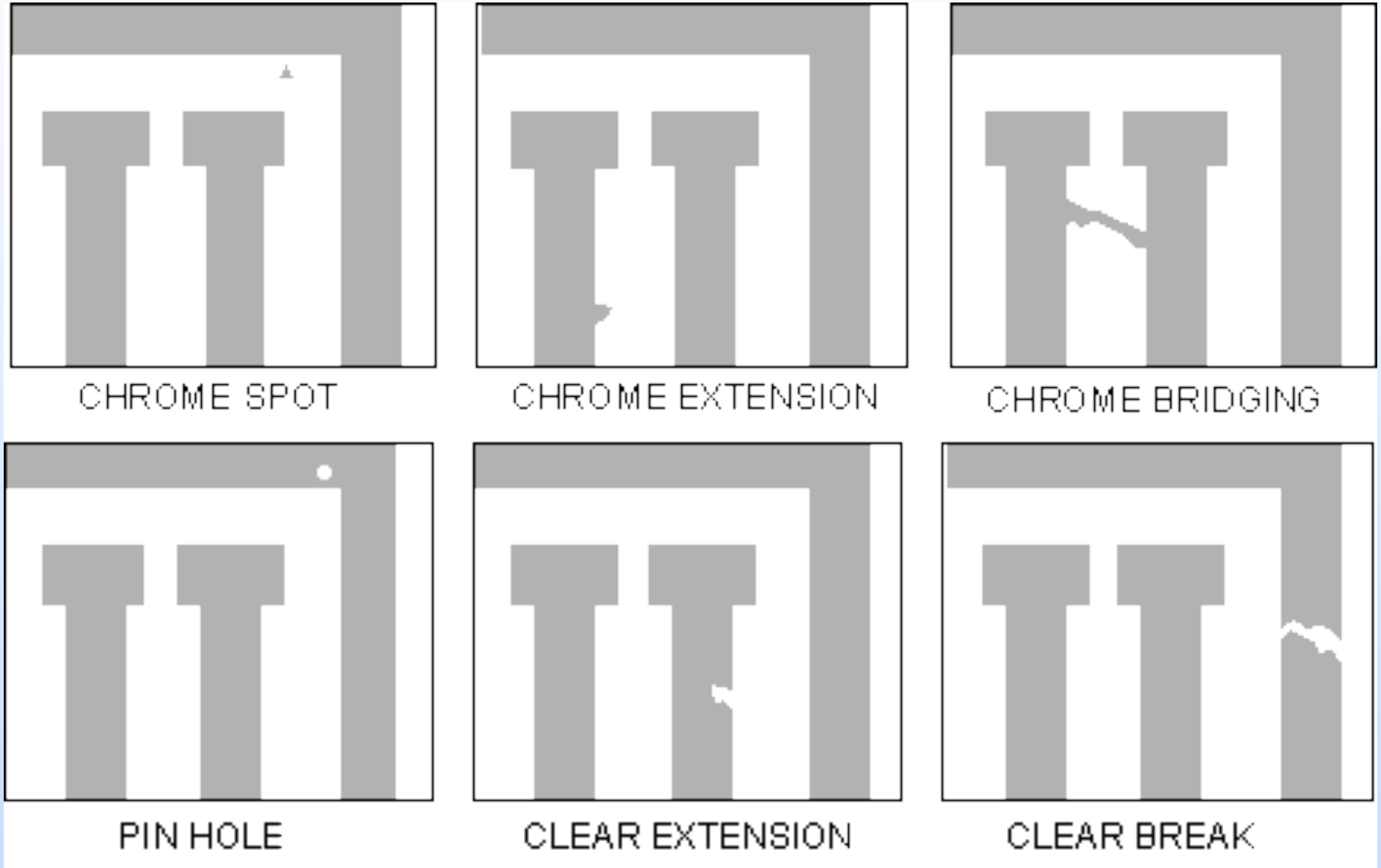
Chrommasken in der optischen Lithographie

- Quarzplatte mit einer strukturierten Chromschicht (Absorber)
    - Quarzplatte ist transparent für UV
    - Chrom absorbiert UV

- Produktion mit Elektronenstrahl-Schreiber
- Kosten: ca. 500 – 3000 CHF für 5‘‘ Maske



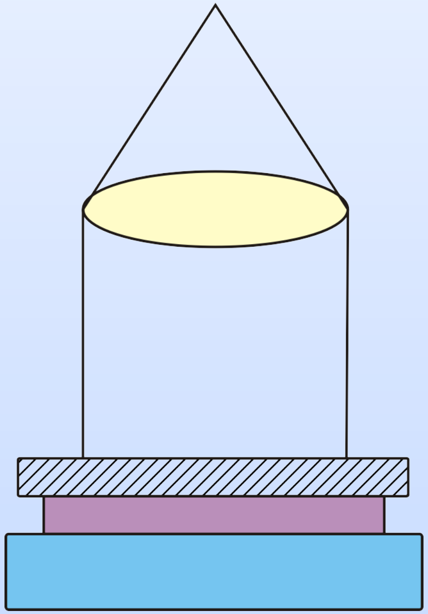
Masekendefekte



- Maskenreparatur nur mit FIB Technik

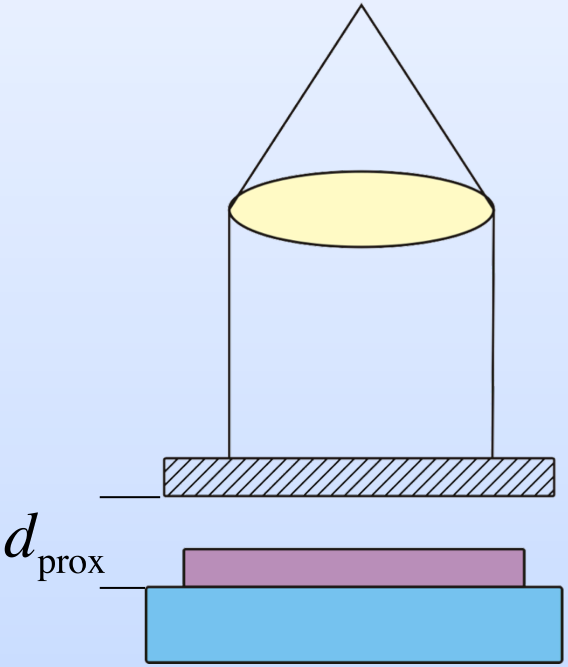
Belichtungsverfahren

Contact printing



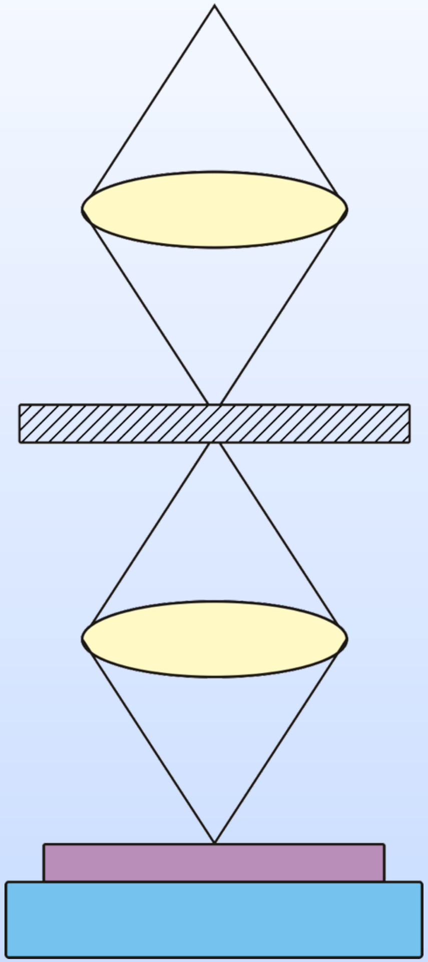
- Defekten auf Wafer
- Lebensdauer der Maske

Proximity printing



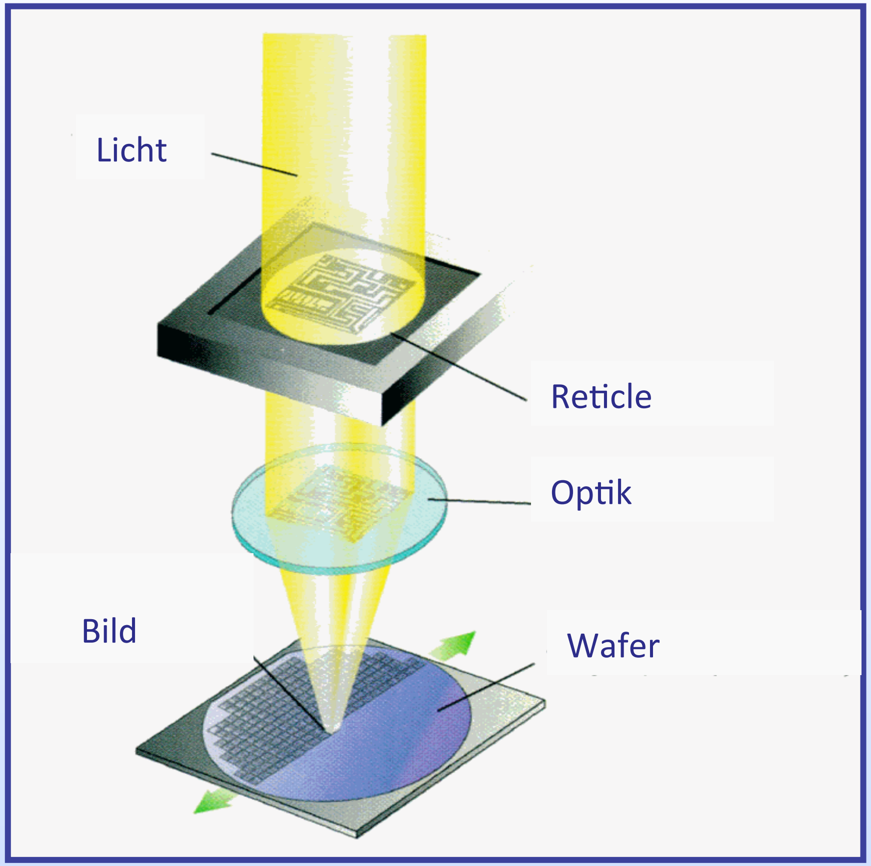
- Reduzierte Auflösung

Projection printning



- keine direkte Kontakt Maske/Wafer
- verbesserte Auflösung

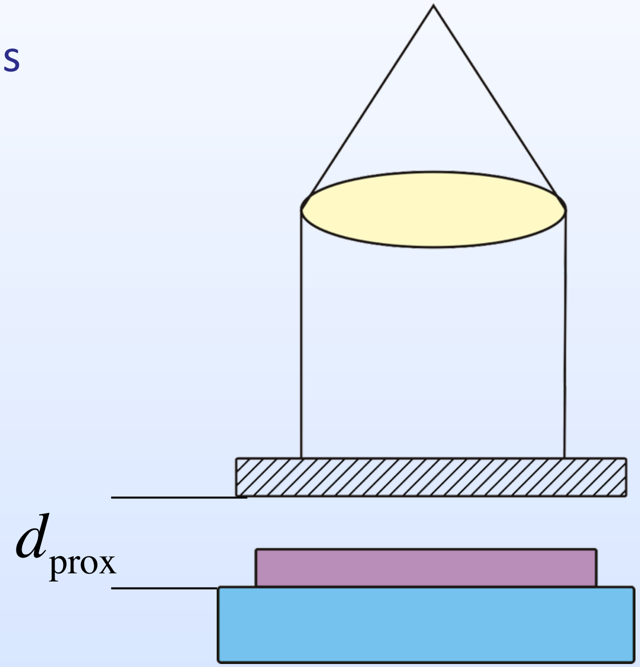
Step and Repeat

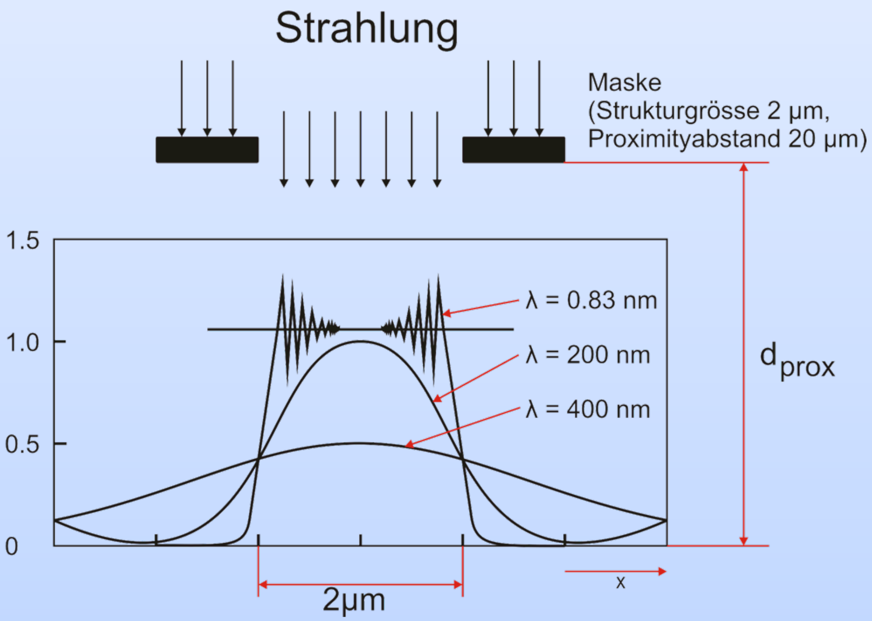


- die Strukturen auf dem Reticle werden beim Stepper verkleinert abgebildet
- ein Reticle muss mehrfach auf einen Wafer belichtet werden (Step and Repeat)

Auflösung bei der Schattenprojektion

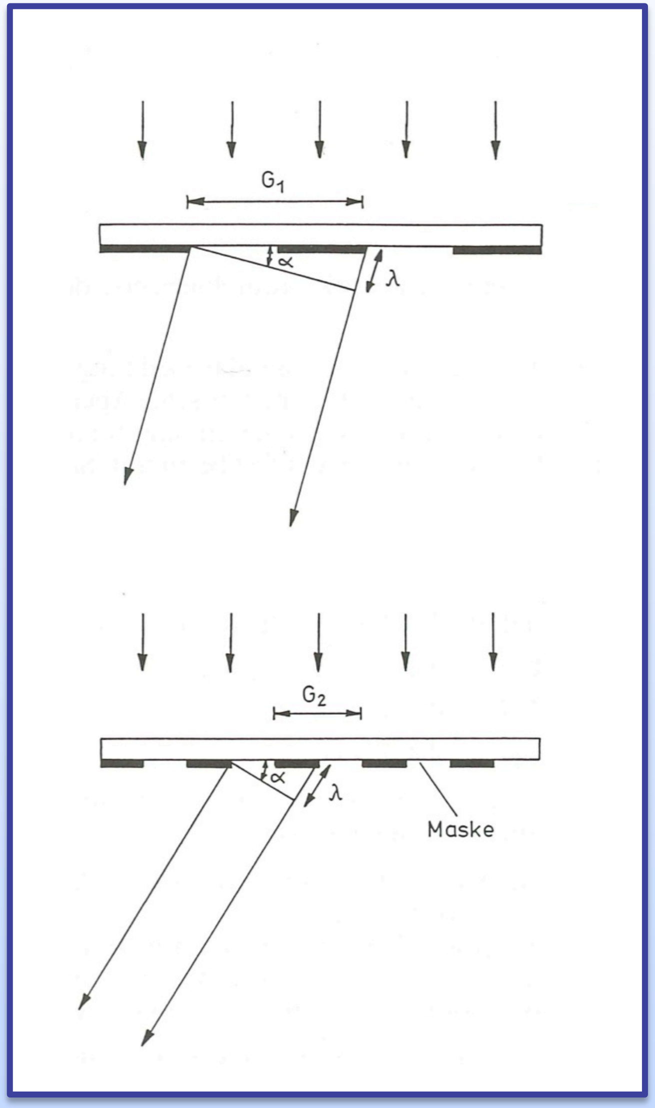
- Physikalische Grenze aufgrund Wellennatur des Lichtes
- Beugung des Lichtes an der Maske, abhängig von:
  - Wellenlänge
  - Proximity Abstand
- Intensitätsverteilung im Lack

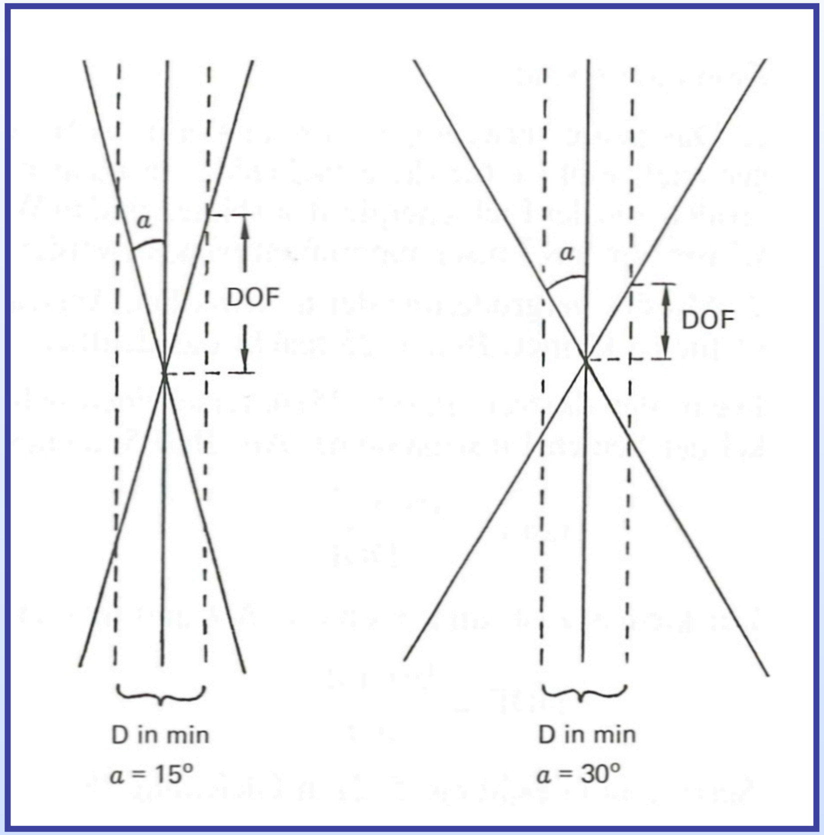




$$\boxed{CD = \sqrt{\lambda d_{\text{prox}}}}$$

Abbildende Projektion





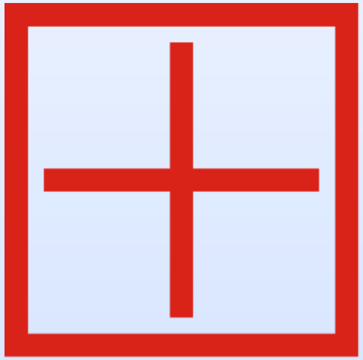
$$\mathrm{CD} = k_1 \frac{\lambda}{NA}$$

$$\mathrm{DOF} = k_2 \frac{\lambda}{NA^2}$$

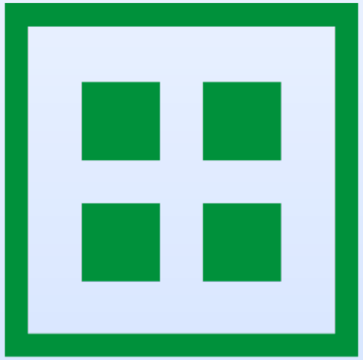
Alignment

Strukturübertragung über mehrere Masken erfordert deren jeweilige Justage zum Substrat

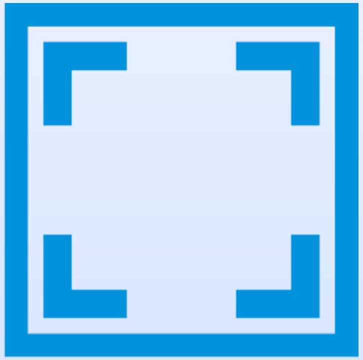
- Durchführung im Mask – Aligner
- Substrat und Maske sind in x, y, und ϕ beweglich



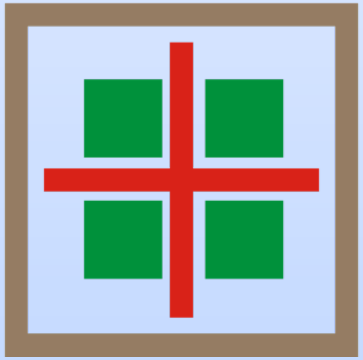
Maske 1



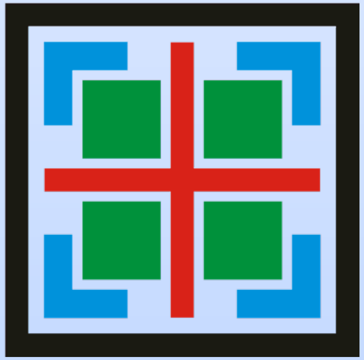
Maske 2



Maske 3

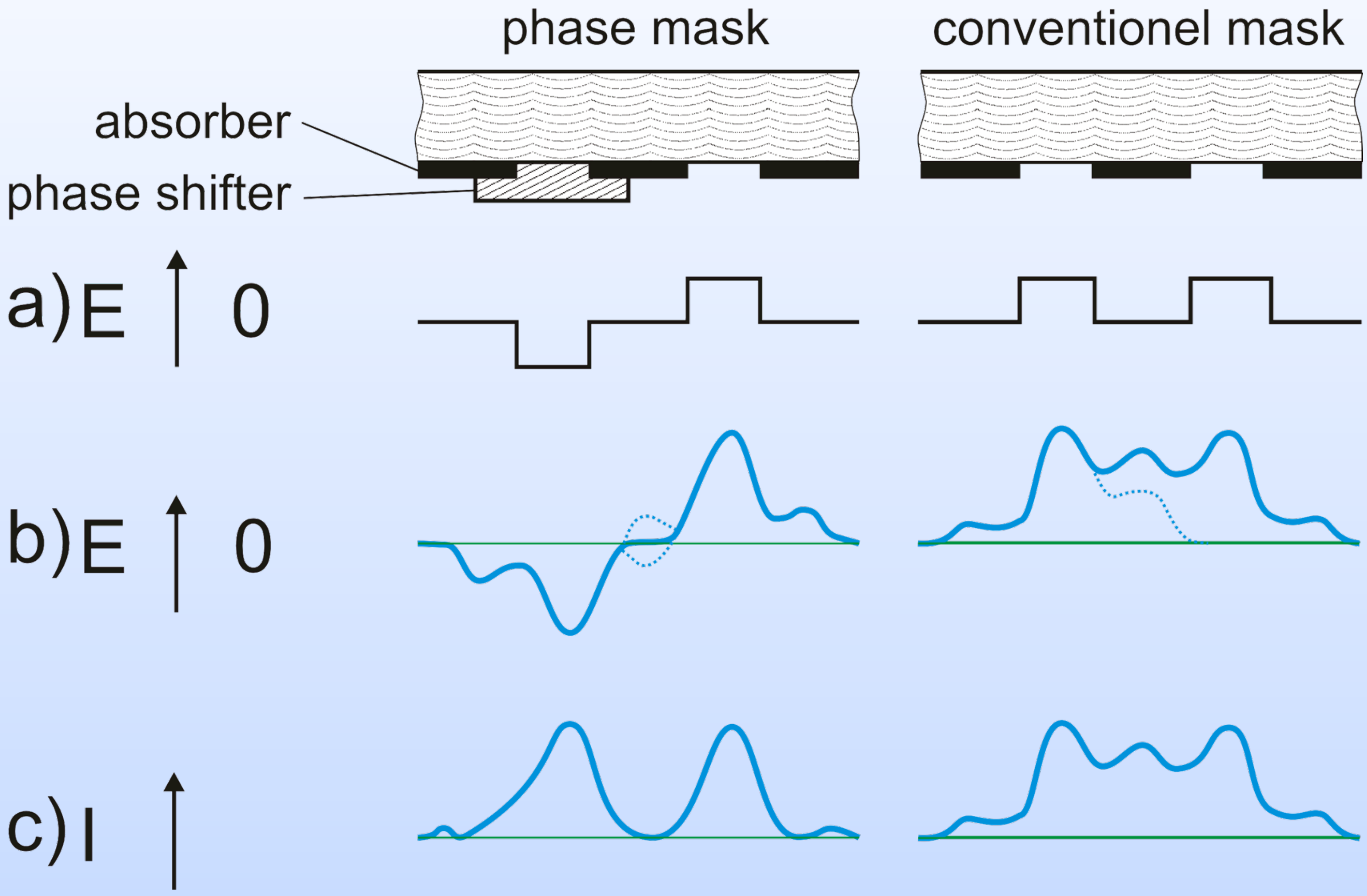


Doppelbelichtung 1 + 2



Dreifachbelichtung 1 + 2 + 3

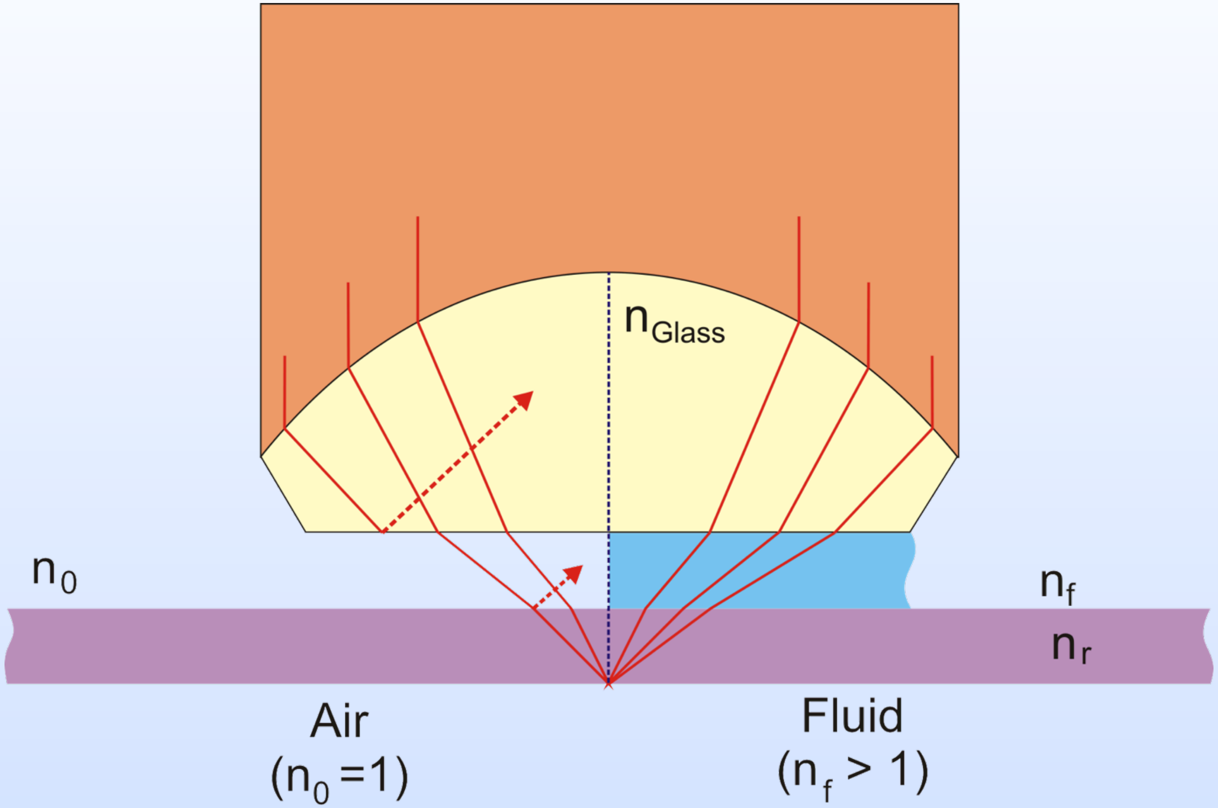
Phasenschiebende Maske



Immersion – Lithographie

$$\mathrm{CD} = k_1 \frac{\lambda}{NA}$$

$$NA = n \sin\alpha$$



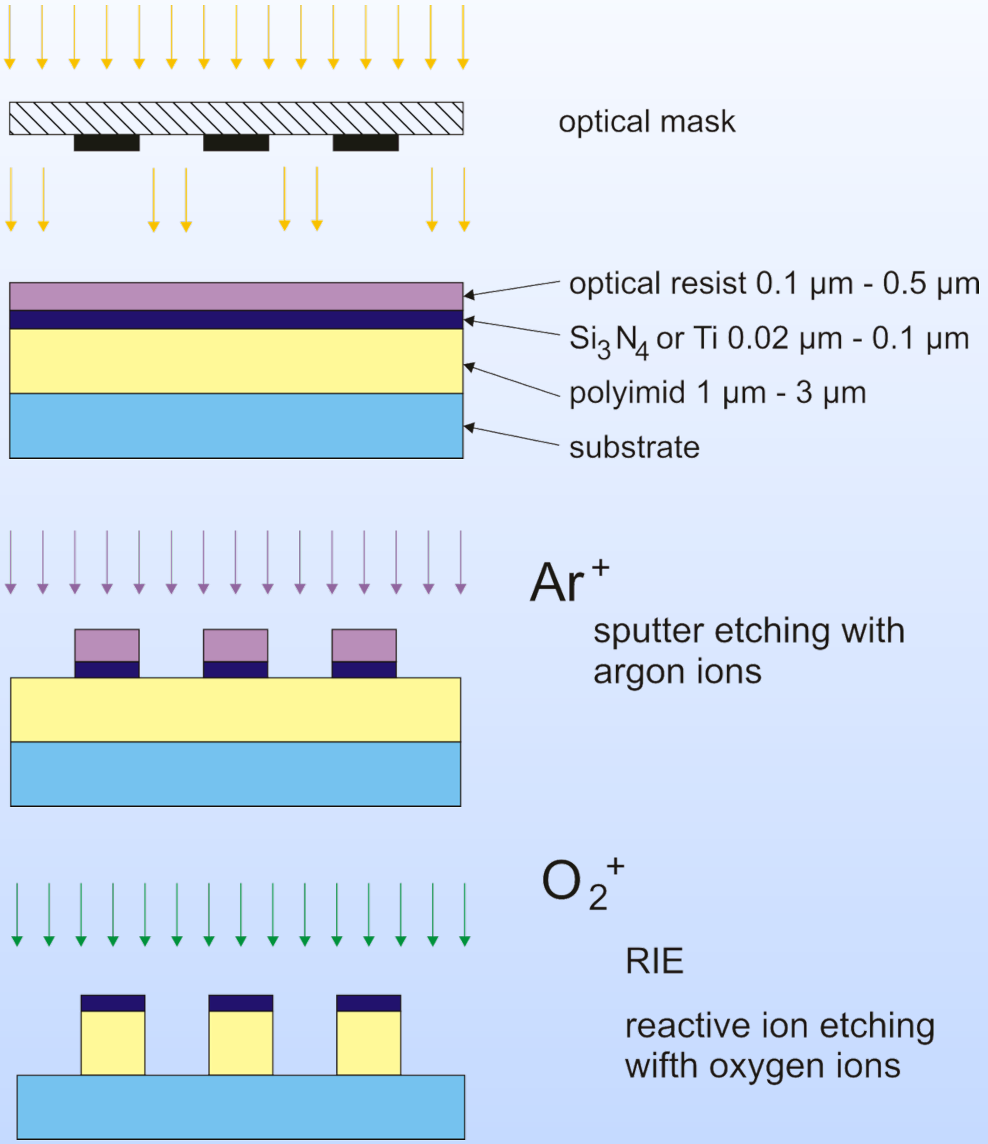
- Vergrösserung der numerischen Apertur durch Medium mit Brechungsindex > 1
- Theoretische Auflösung für 193 nm Wellenlänge steigt damit auf 35 nm
- Bei Reduktion der Wellenlänge auf 157 nm ist aber das Wasser nicht transparent

„Tri-Level-Prozess“

Mehrlagen-Resist

- sehr dünne Schicht, die optisch strukturiert wird
- darunter liegende Schichten werden durch Ätzverfahren strukturiert

→ kleine Fokustiefe!



Elektronenstrahl – Lithographie

Anwendung der Elektronenstrahl-Lithographie

- Maskenherstellung
- Nanotechnologie

Abrastern einer 5“ Maske mit einem Elektronenstrahl von 2 nm Breite

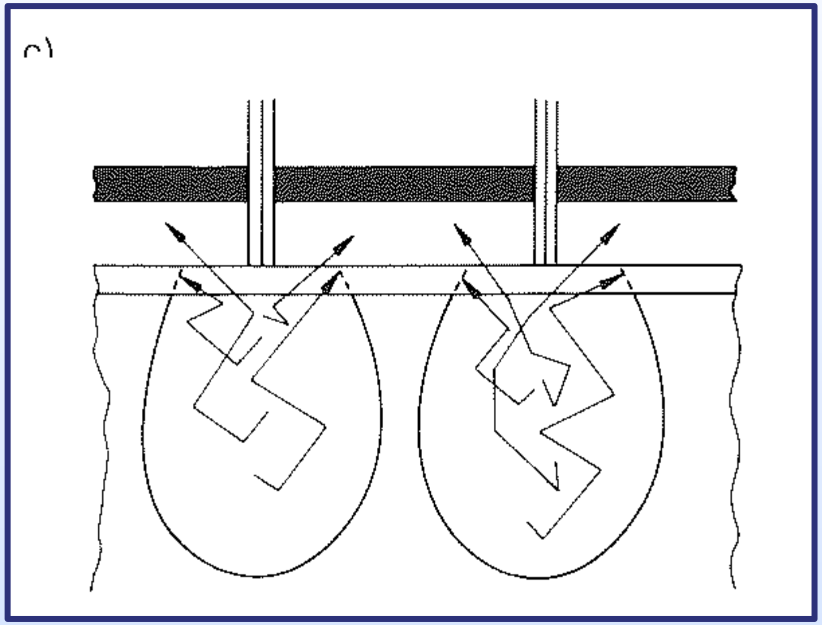
- 120 mm = 120×10^6 nm
- 60×10^6 Zeilen oder 7‘200 km Schreiblänge bei 2 nm Strahlbreite
- $7'200 \times 10^{12}$ nm 3.6×10^{15} Pixel

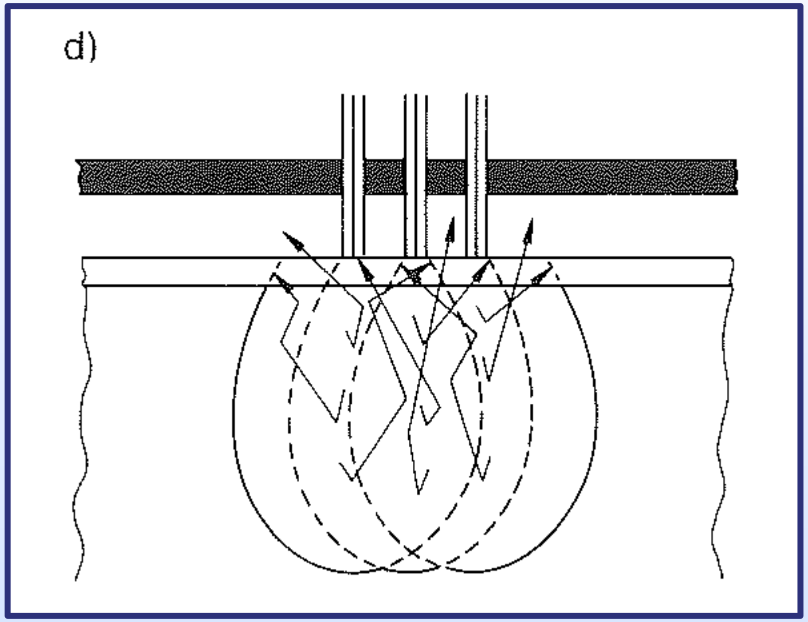
Schreibstrategien:

- Vektorscan
- Geformter Strahl

Vistec VB300 E-Beam System, NIST

Auflösung der Elektronenstrahl Lithographie: Proximity Effekt





Stralhdurchmesser nicht entscheidend

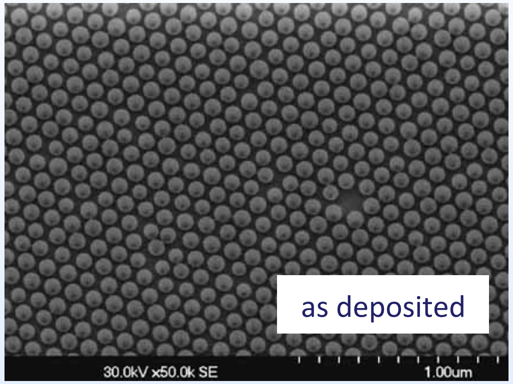
Proximity Effekt

- Vorwärtsstreuung der Elektronen im Resist
- Rückstreuung der Elektronen vom Substrat

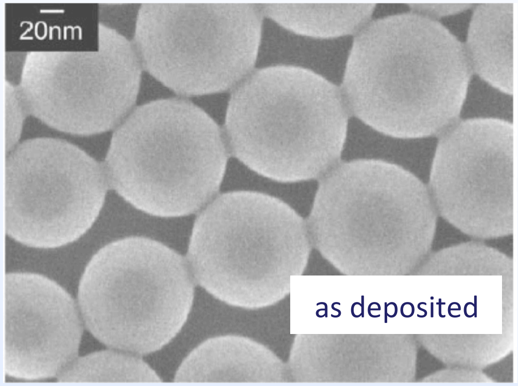
Einflusse auf Proximity Effekt

- Beschleunigungsspannung
- Dicke und Atomgewicht des Resists
- Atomgewicht des Substratmaterials
- Angepasstes Dosis

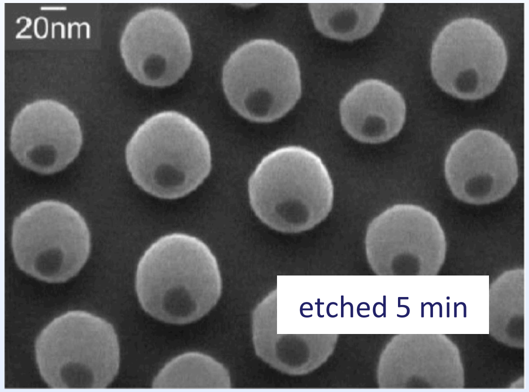
Colloid Lithography



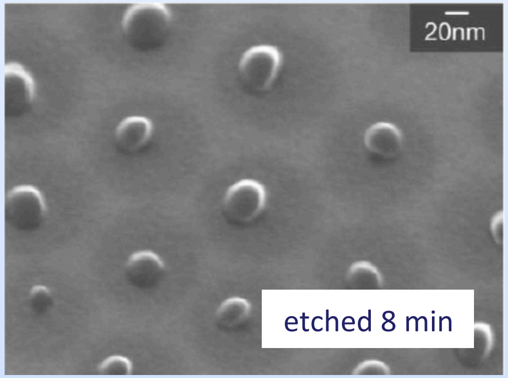
as deposited



as deposited



etched 5 min



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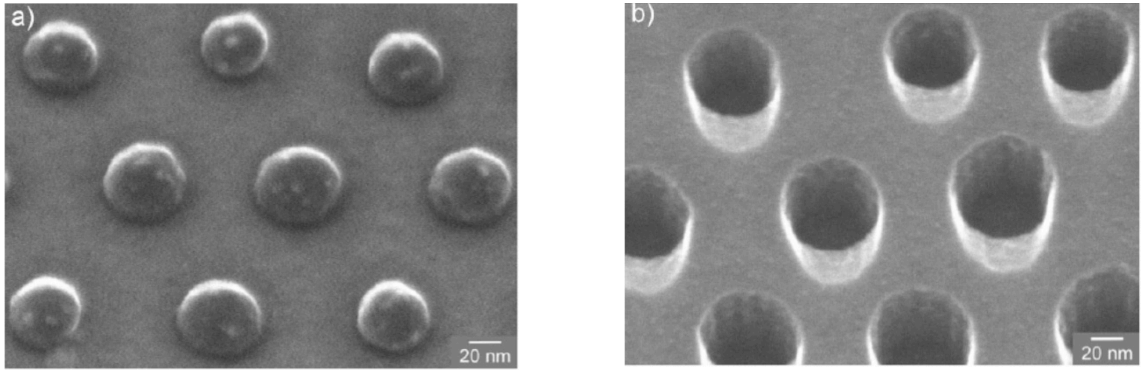

- Hexagonally ordered arrays of non-close-packed nanoscaled spherical polystyrene (PS) particles followed by isotropical etching

A. Plettl et al., Advanced Functional Materials, V19, 2009, p. 3279