6 Photolithography

Objectives

- 列出組成光阻(photoresist)的四個成分
- 敘述正光阻(+PR)和負光阻(–PR)的差異
- 敘述微影製程(photolithography)的順序
- 列出四種對準(alignment)和曝光(exposure) 系統
- 敘述晶圓在步進機整合系統(track-stepper integrated system)中的移動方式
- 說明解析度(resolution)和景深(depth of focus)、波長(wavelength)及數字孔徑(numerical aperture)的關係

Introduction

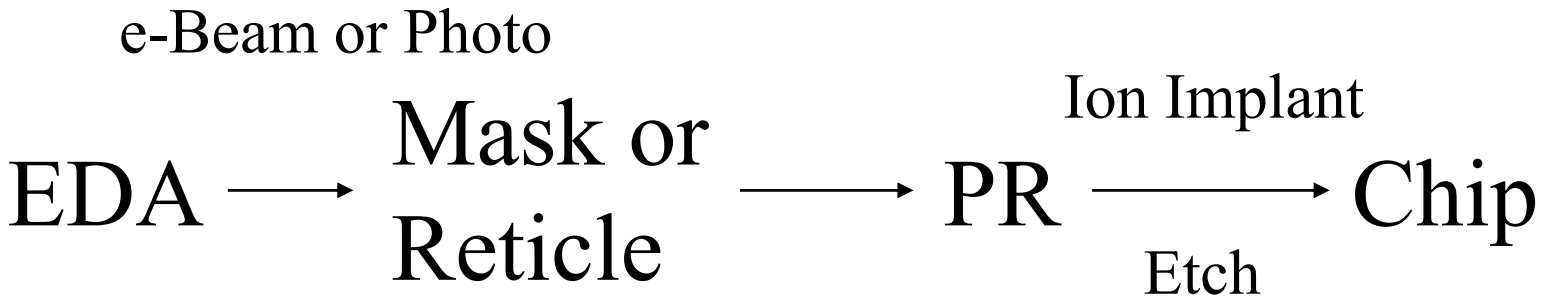
微影技術(Photolithography)

- 暫時塗佈光阻在晶圓的表面
  - 將設計好的圖案轉印到光阻上
  - 是IC製程中最重要的步驟
  - 佔晶圓製程時間的40到50%
- 決定縮小生產晶圓的最小圖形尺寸

Applications of Photolithography

- 主要運用： IC圖案化製程(patterning process)
- 其他運用：印刷電路板,標示牌,金屬板等

IC Fabrication

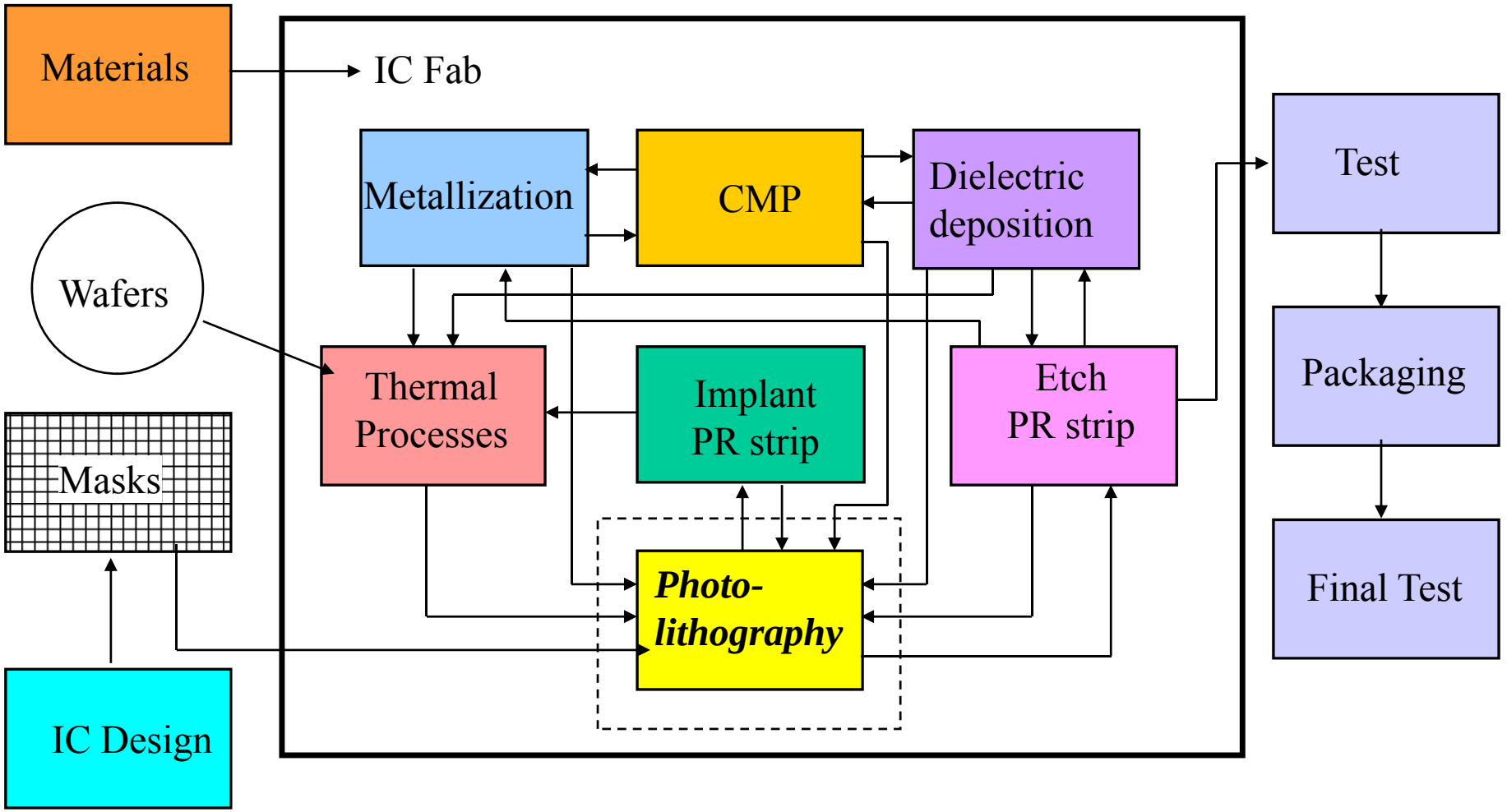


Photolithography

EDA: Electronic Design Automation

PR: Photoresist

IC Processing Flow



Photolithography Requirements

- 高解析度(Resolution)
- 高感光度
- 精確的對準性(Alignment)
- 精確參數控制製程
- 低缺陷密度

Photoresist

- 照片感光材料
- 暫時塗佈在晶圓表面
- 透過曝光將圖案轉印在晶圓上
- 與塗佈在照相機底片上的感光材料相似

Photoresist

負光阻

（Negative Photoresist)

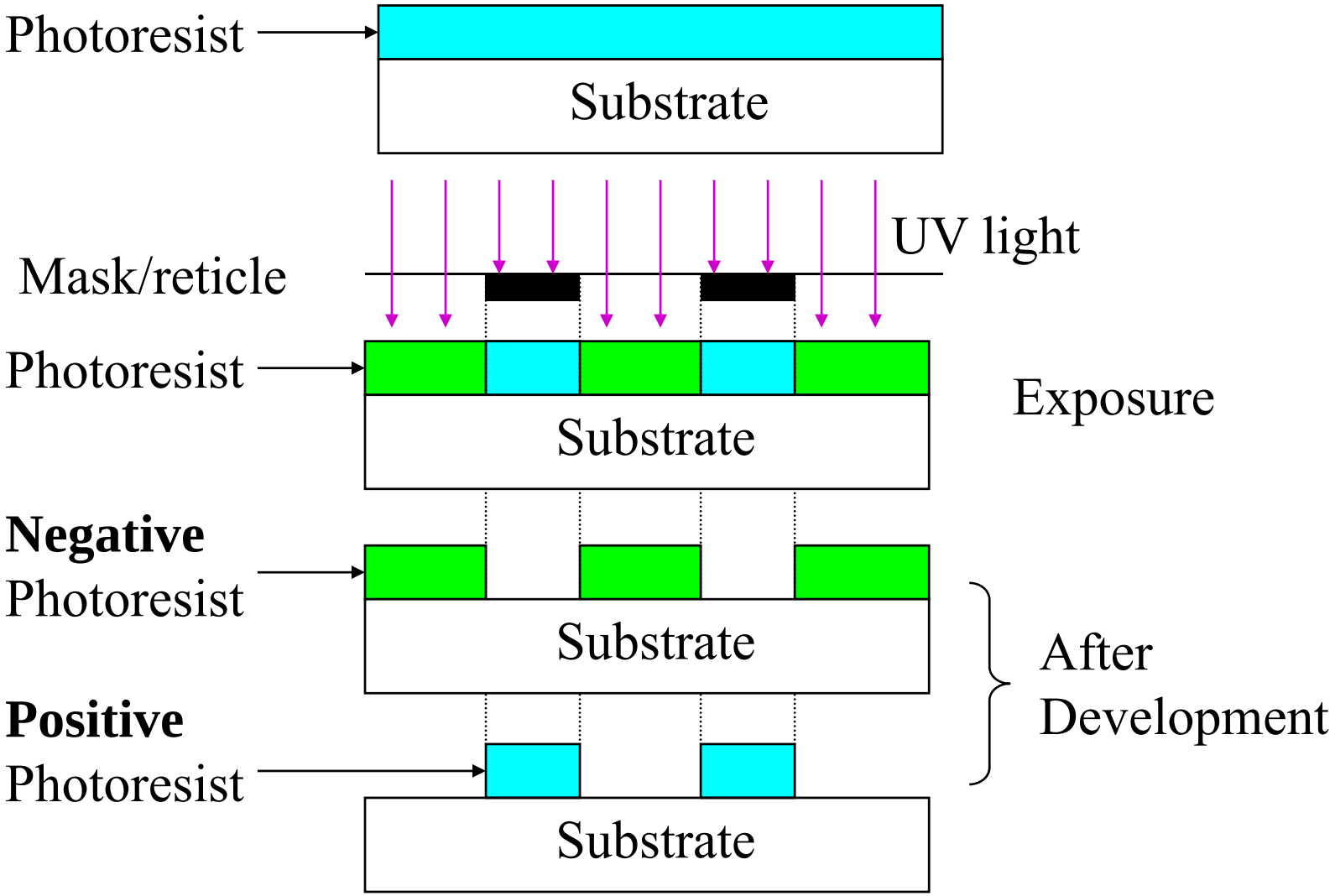
- 曝光部分不溶解
- 顯影之後, 未曝光部分溶解
- 便宜

正光阻

（Positive Photoresist)

- 曝光部分溶解
- 顯影之後, 曝光部分溶解
- 高解析度

Negative and Positive Photoresists



Photoresist Chemistry

- 開始於印刷電路
- 於1950適用於半導體工業
- 圖案化製程(patterning process)的關鍵
- 正光阻及負光阻

Photoresist Composition

- 聚合體(Polymer)
- 溶劑(Solvents)
- 感光劑(Sensitizers)
- 添加劑(Additives)

Polymer

- 有機固態材料
  - 將圖案轉印在晶圓表面
  - 當暴露在紫外光(UV light)下因為光化學反應改變可溶性.
  - 正光阻：由不溶解到溶解
  - 負光阻：由溶解到不溶解

Solvent

- 溶解聚合體的液體
- 利用旋轉方式形成薄光阻層

Sensitizers

- 控制並調整光阻在曝光過程中的反應
- 決定曝光時間及強度

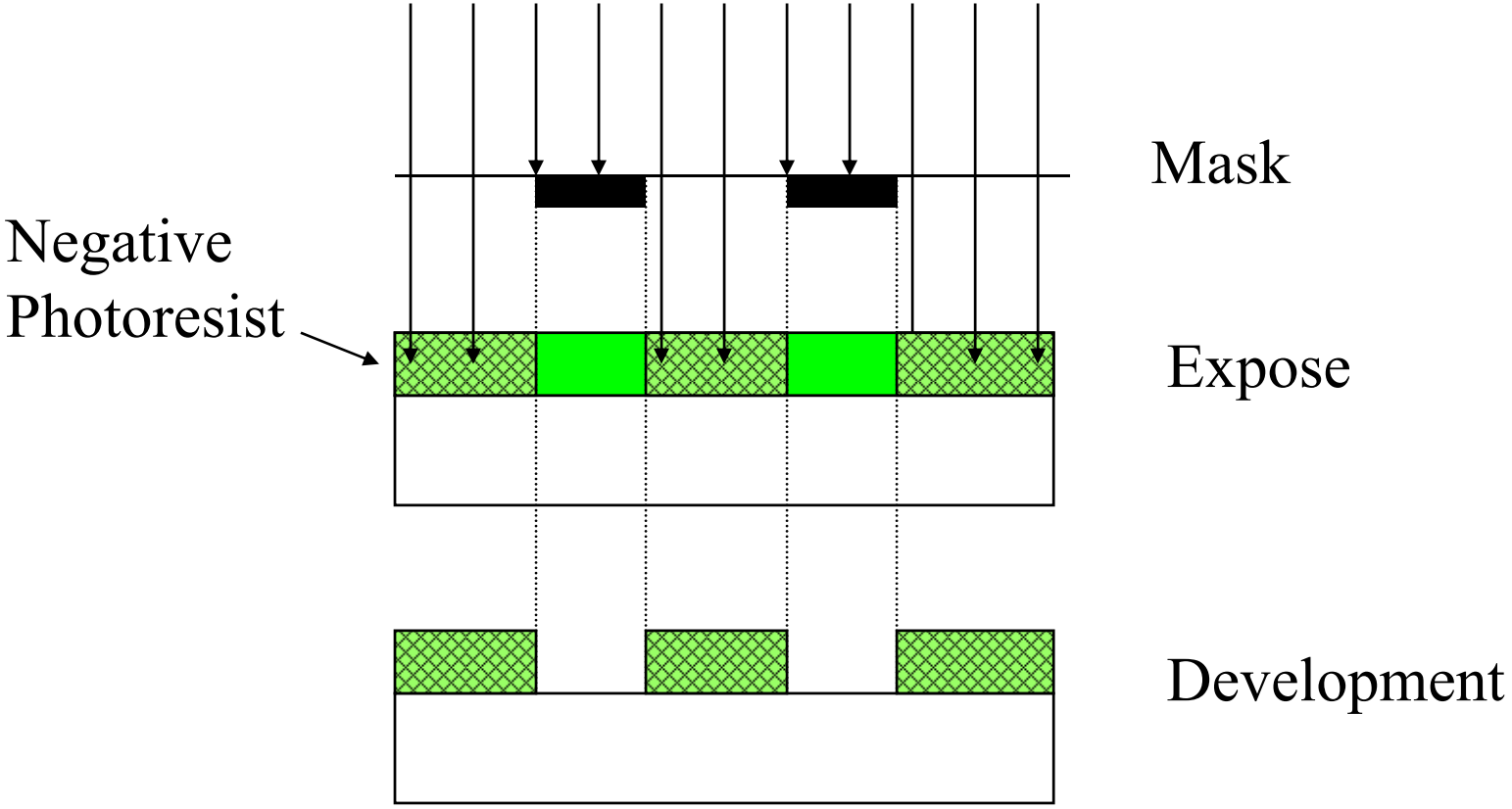
Additives

- 加入不同的化學藥劑以達到理想的結果, 例如染料可減少反射光.

Negative Resist

- 大多數的負光阻(negative PR)是聚異戊二烯(polyisoprene)
- 曝光光阻變成交連(cross-linked)聚合物
- 交連聚合物有高的化學蝕刻抵抗力
- 未曝光部分在顯影溶劑中被分解

Negative Photoresist

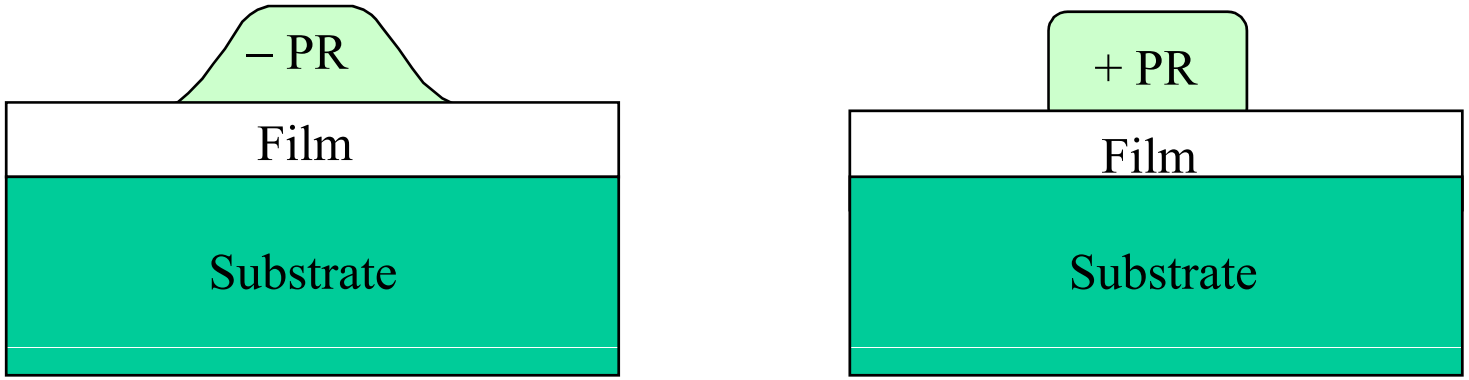


Negative Photoresist

Disadvantages

- 聚合物吸收顯影溶劑
  - 光阻膨脹(swelling)限制了解析度
  - 主要溶劑為二甲苯(xylene)造成環保及安全問題

Comparison of Photoresists



Positive Photoresist

- 曝光部分在顯影劑中被分解
- 造成與光罩相同的圖像
- 高解析度
- 在IC fabs中被普遍使用

Positive Photoresist

- 酚醛樹脂聚合物(Novolac resin polymer)
- 醋酸鹽型式溶劑(Acetate type solvents)
- 感光劑(Sensitizer)交連(cross-linked)在樹脂中(resin)
- 光能會分解感光劑並破壞交連結構(cross-links)
- 樹脂變得能夠溶解

正光阻反應式

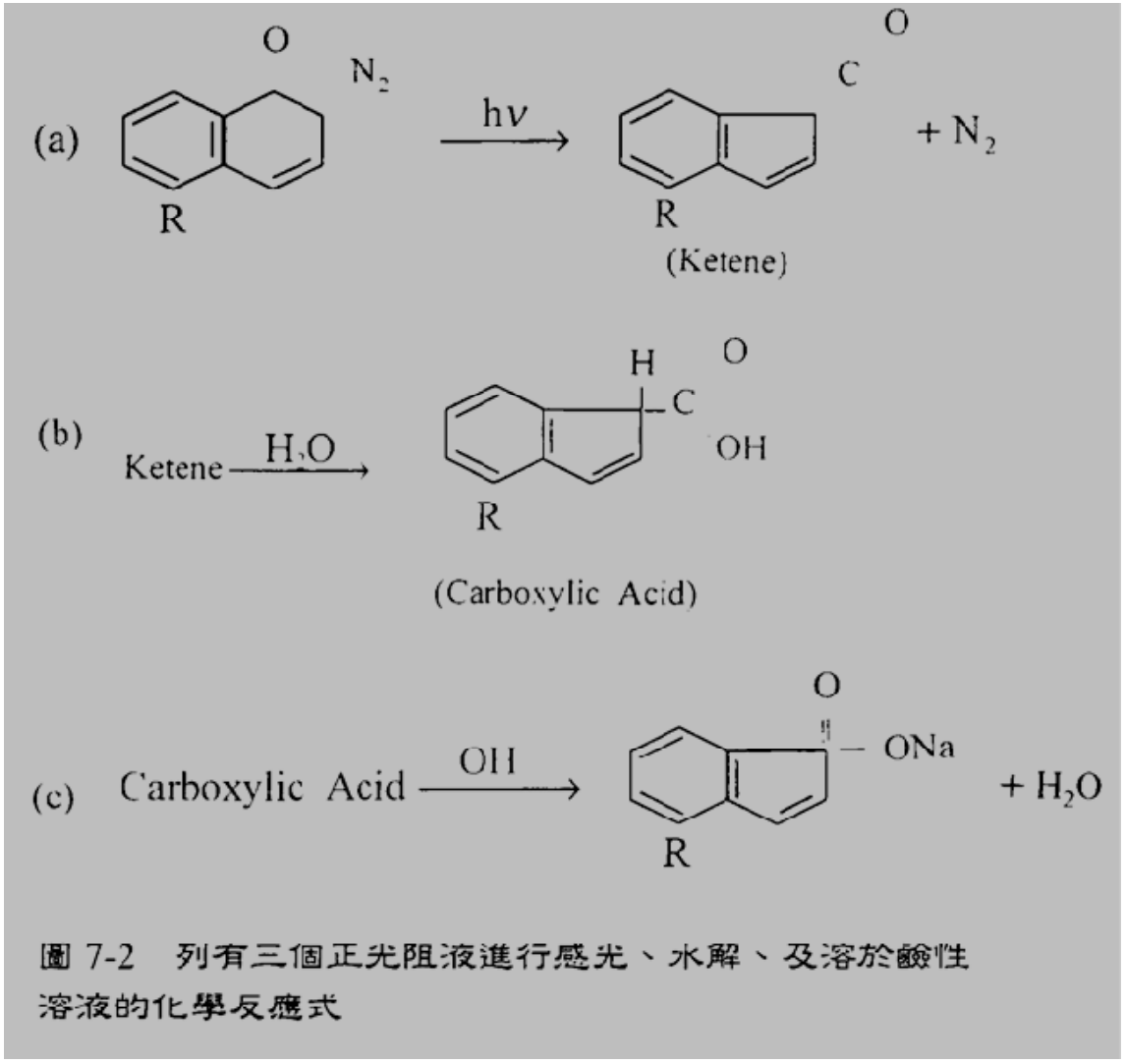


圖 7-2　列有三個正光阻液進行感光、水解、及溶於鹼性溶液的化學反應式

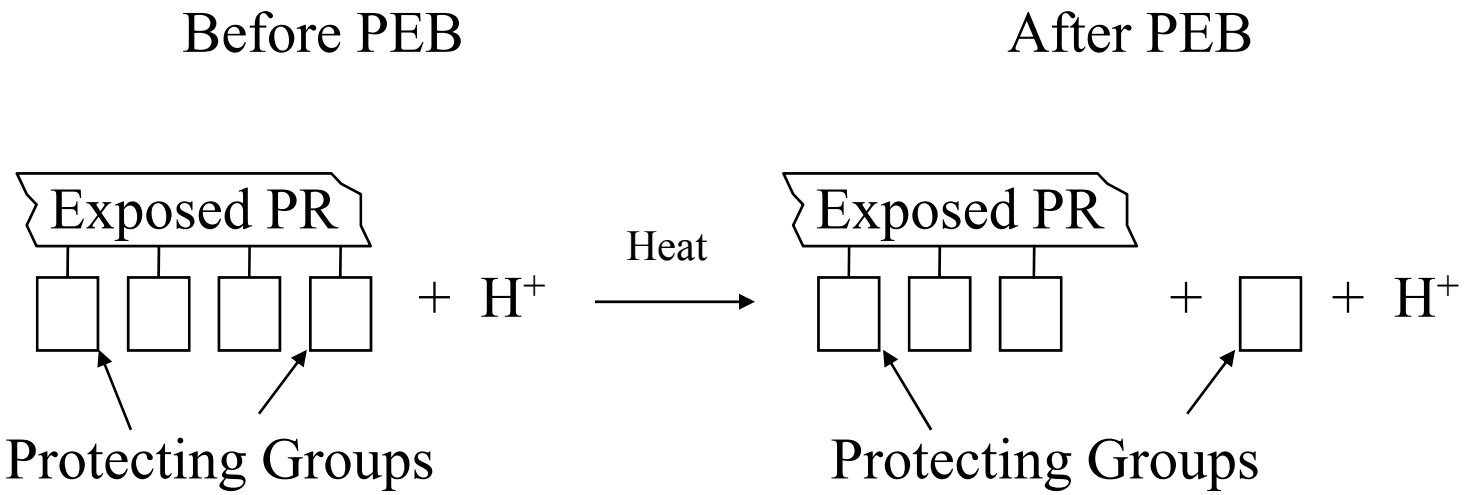
Chemically Amplified Photoresists

- 深紫外線(DUV), $\lambda \leq 248$ nm
- 光源：準分子雷射(excimer lasers)
- 光強度低於高壓水銀燈中的I-line (365 nm)
- 需要不同種類的光阻

Chemically Amplified Photoresists

- 催化作用增強光阻感光度
  - 在DUV光線照射下造成光阻產生光酸(photo-acid)
  - 烘烤(PEB)製程中,催化反應下會驅使光酸(acid)擴散
- 光酸使保護群移動
- 曝光部分被顯影劑分離

Chemically Amplified Photoresist



Requirement of Photoresist

- 高解析度
  - 光阻薄膜越薄解析度越高
  - 光阻薄膜越薄對抗蝕刻和離子佈植(ion implantation)能力越低
- 高抗蝕刻能力
- 高附著力(adhesion)
- 製程自由度(latitude)較寬
  - 對於製程條件改變有較高容許限度

Photoresist Physical Properties

- 光阻必須能容許較寬製程條件
- 塗佈(Coating), 旋轉(spinning), 烘烤(baking), 顯影(developing).
- 抗蝕刻能力(Etch resistance)
- 離子佈植限制(Ion implantation blocking)

Photoresist Performance Factor

- 解析度Resolution
- 附著力Adhesion
- 曝光速度Expose rate, Sensitivity and Exposure Source
- 製程自由度Process latitude
- Pinholes
- 微粒和污染物Particle and Contamination Levels
- Step Coverage
- 熱流Thermal Flow

Resolution Capability

- The smallest opening or space that can produced in a photoresist layer.
  - 與特殊製程有關, 包括曝光及顯影製程
  - 越薄解析度越好.
- Etch and implantation barrier and pinhole-free require thicker layer
- 因為聚合物較小的尺寸所以正光阻有較好的解析度

Photoresist Characteristics Summary

Parameter	Negative	Positive
Polymer	Polyisoprene	Novolac Resin
Photo-reaction	Polymerization	Photo-solubilization
Sensitizer	Provide free radicals for polymer cross-link	Changes film to base soluble
Additives	Dyes	Dyes

Photolithography Process

Basic Steps of Photolithography

- 光阻塗佈Photoresist coating
- 對準和曝光Alignment and exposure
- 顯影Development

Basic Steps, Old Technology

- 清洗晶圓Wafer clean
- 脫水烘烤Dehydration bake
- 旋轉塗佈底漆層和光阻
- 軟烘烤Soft bake

} PR coating

- 對準和曝光Alignment and exposure
- 顯影Development
- 圖案檢視Pattern inspection
- 硬烘烤Hard bake

} Development

Basic Steps, Advanced Technology

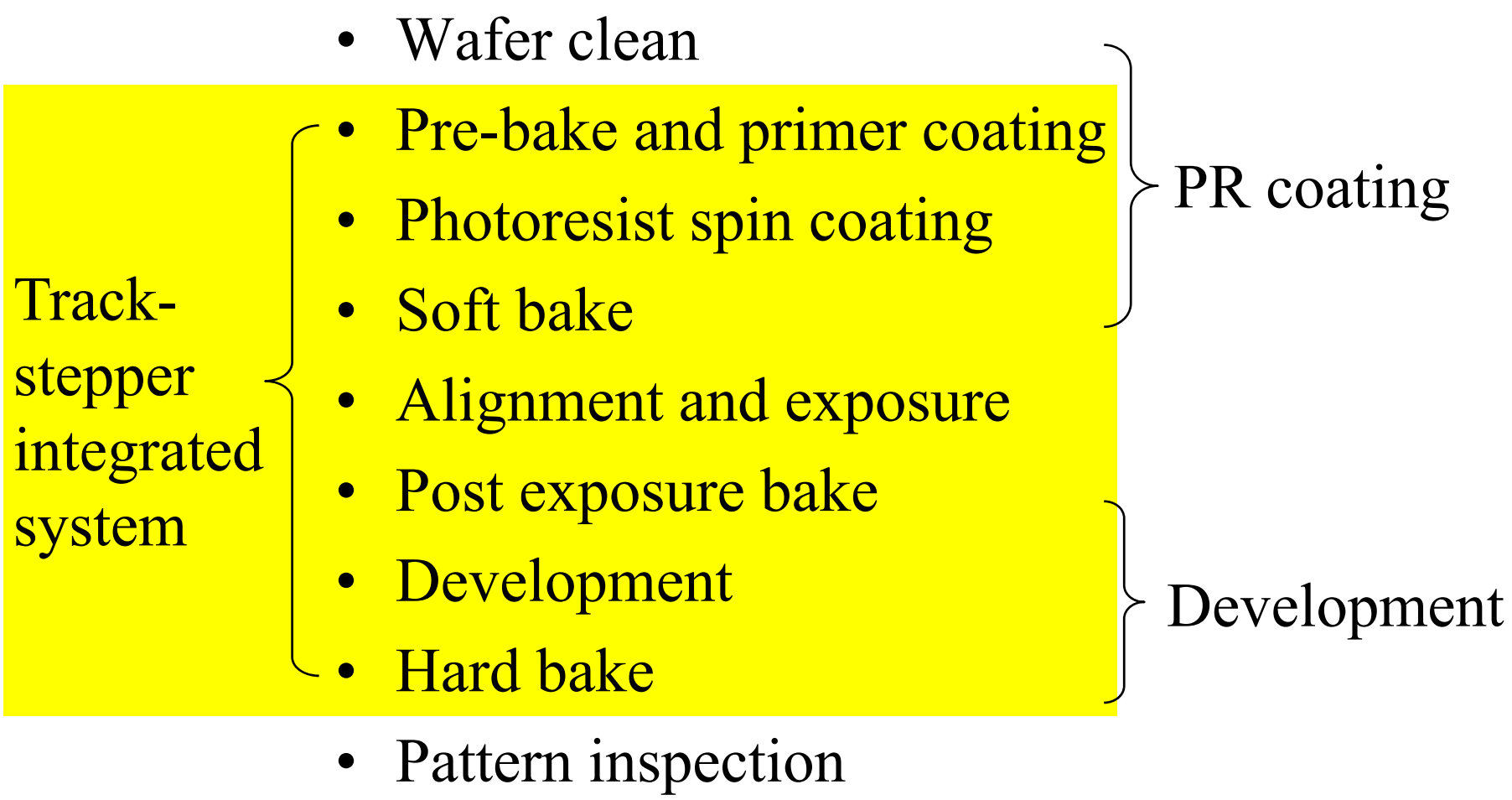
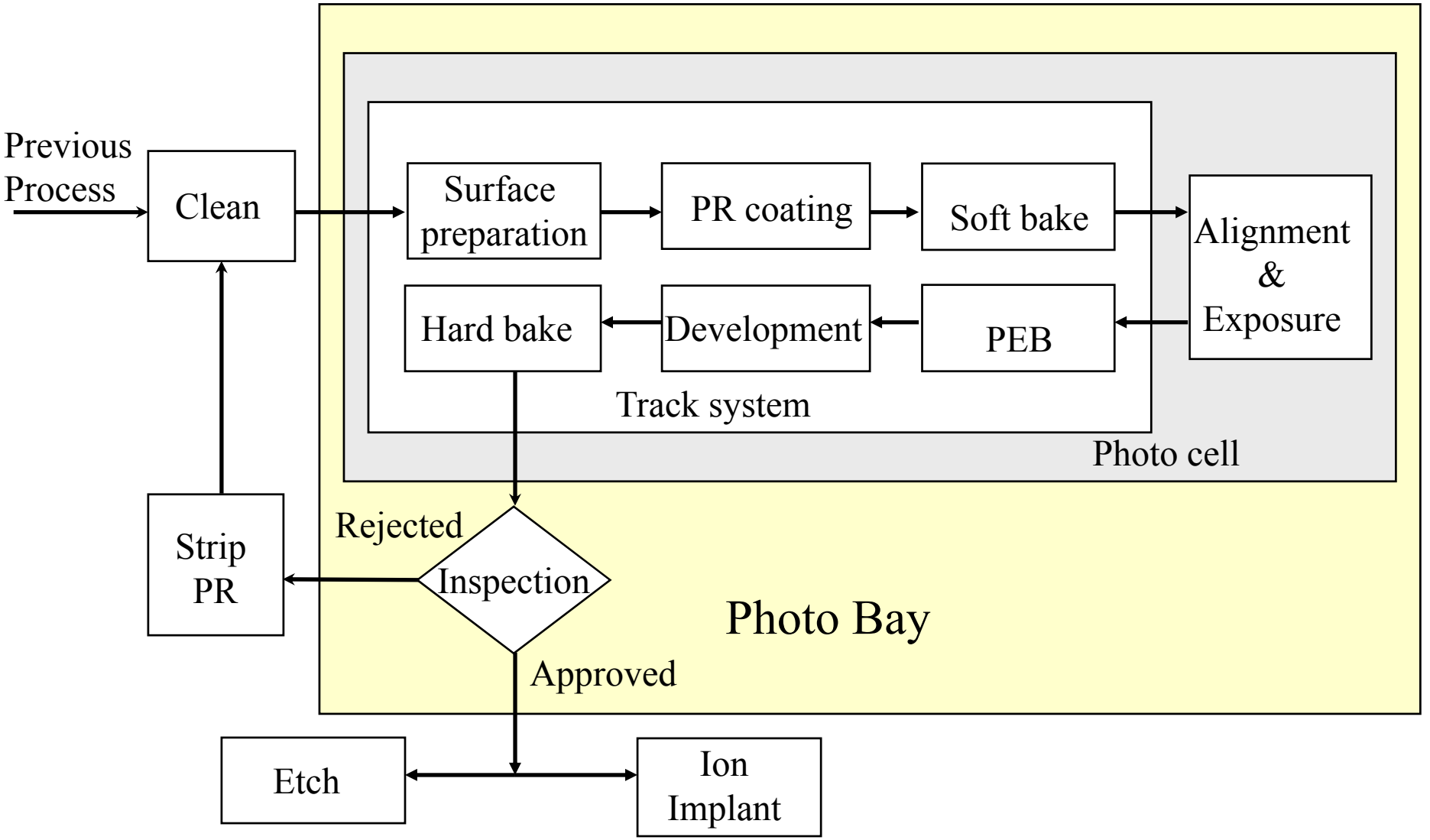
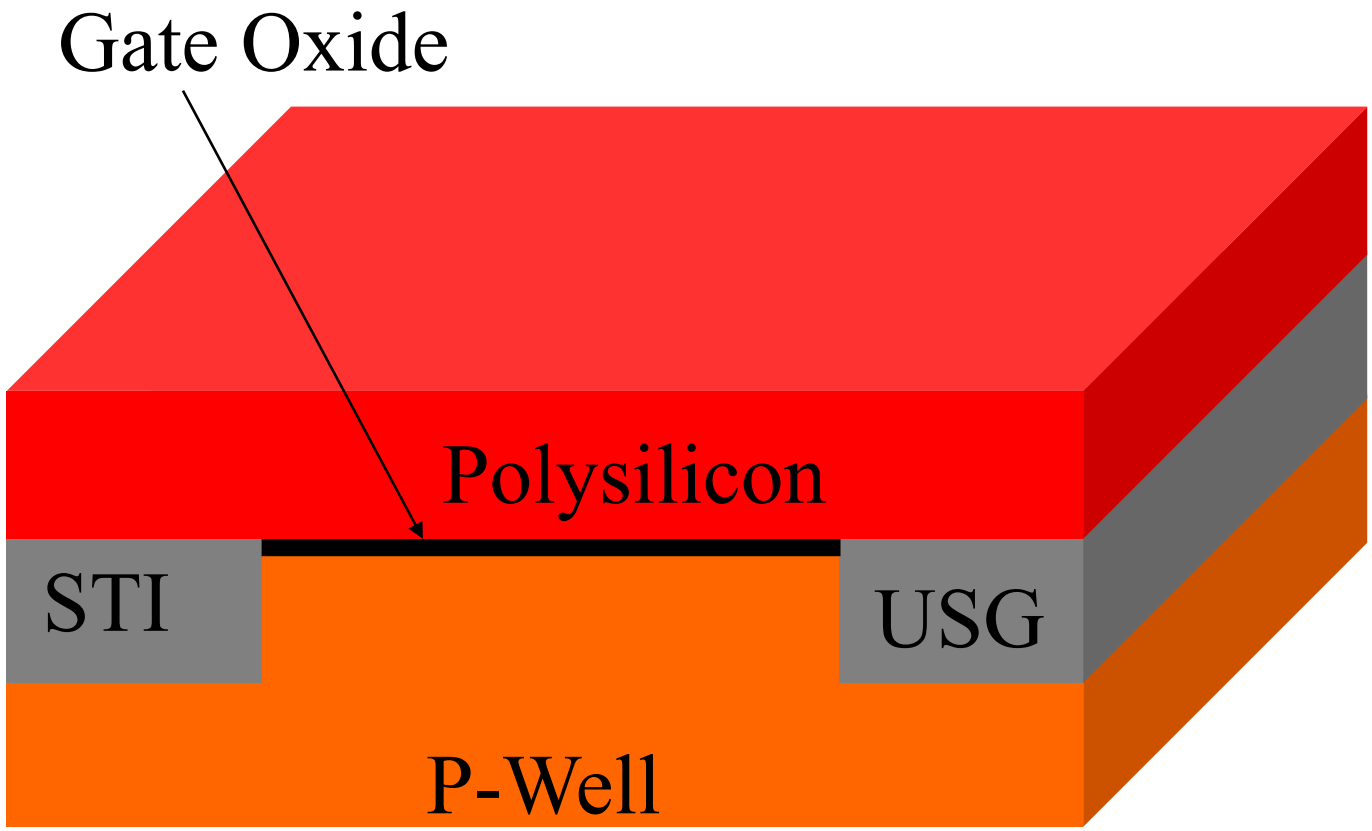


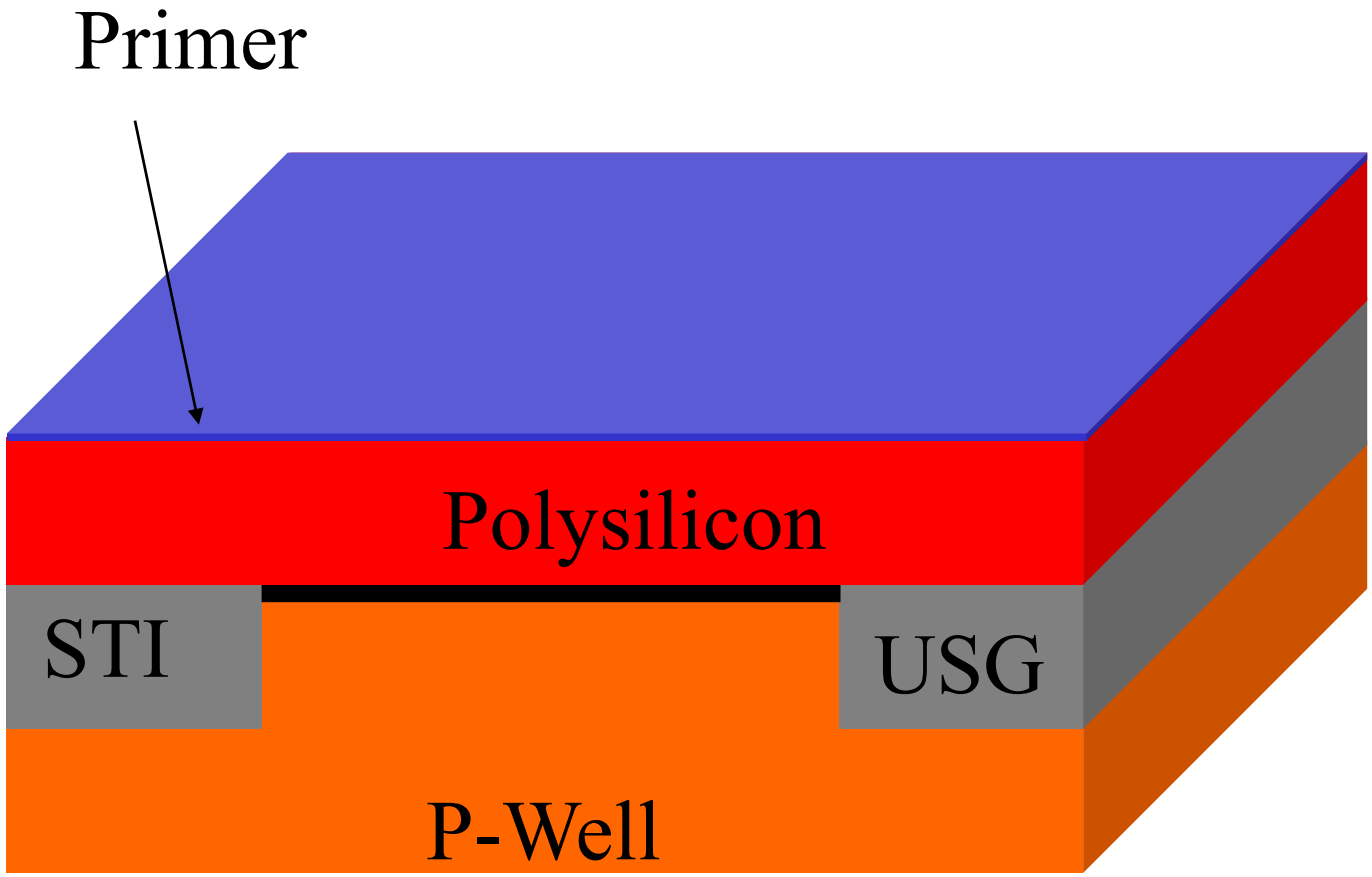
Figure 6.5


Previous Process
Clean
Surface preparation
PR coating
Soft bake
Alignment & Exposure
Hard bake
Development
PEB
Track system
Photo cell
Strip PR
Rejected
Inspection
Photo Bay
Approved
Etch
Ion Implant

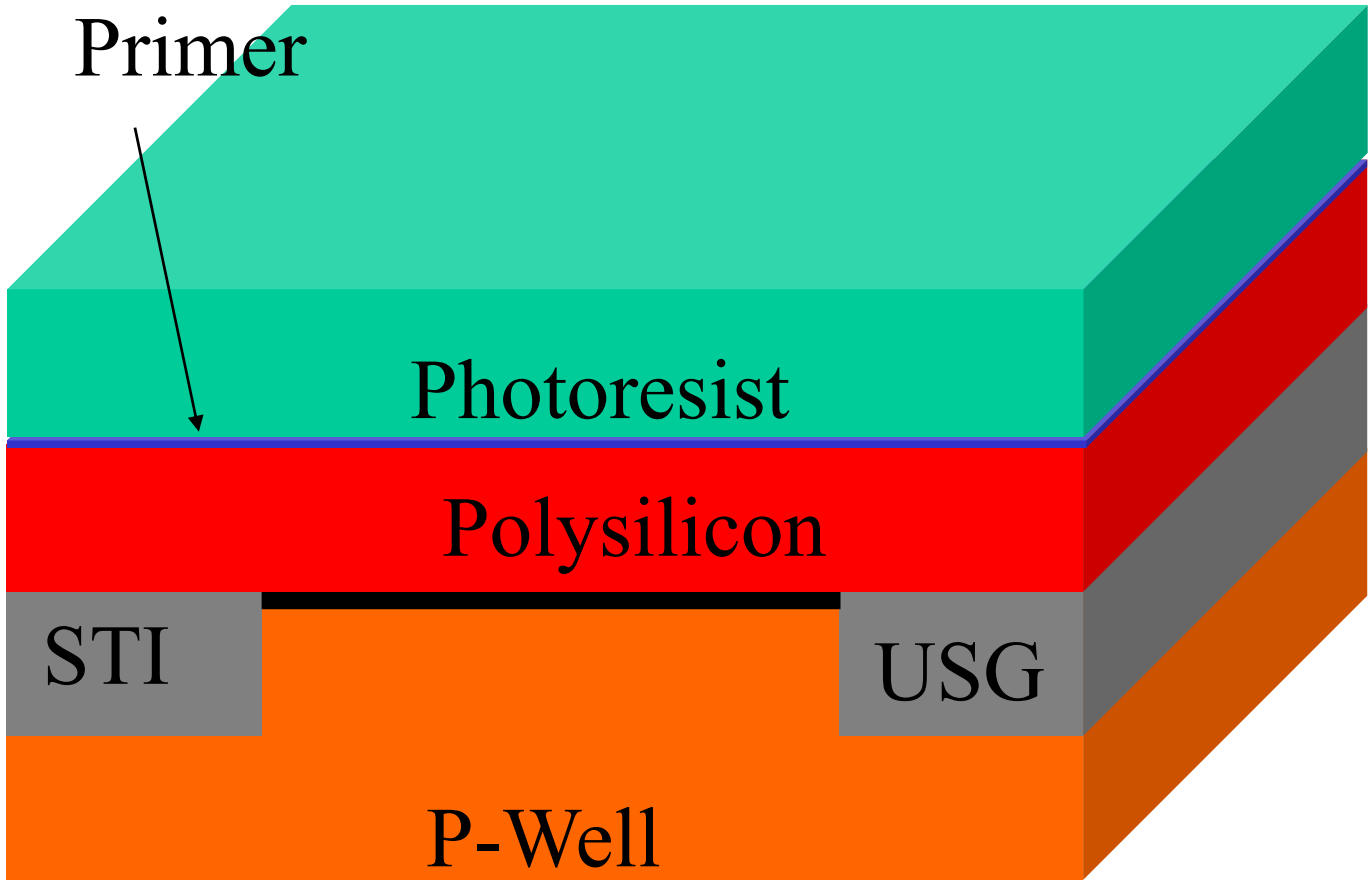
Wafer Clean



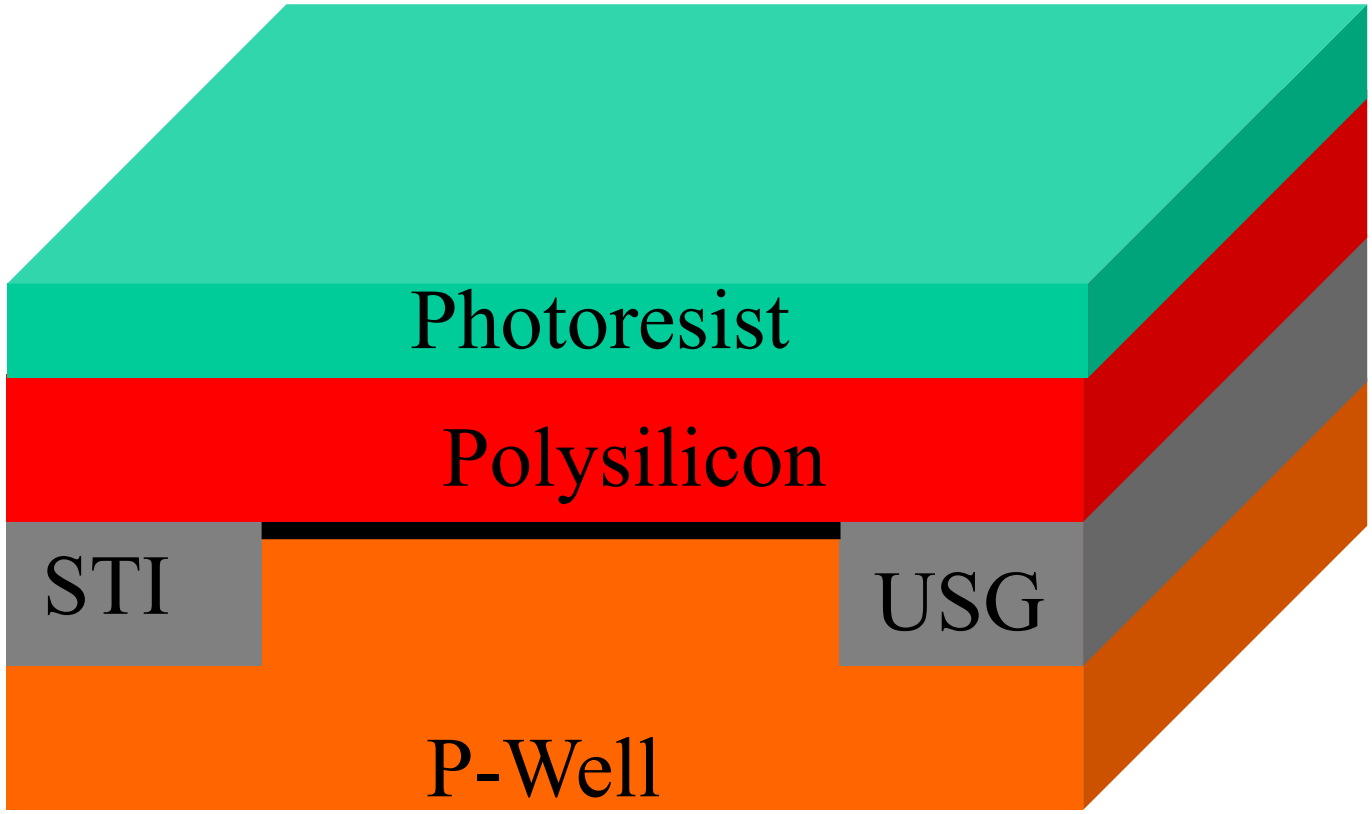
Pre-bake and Primer Vapor



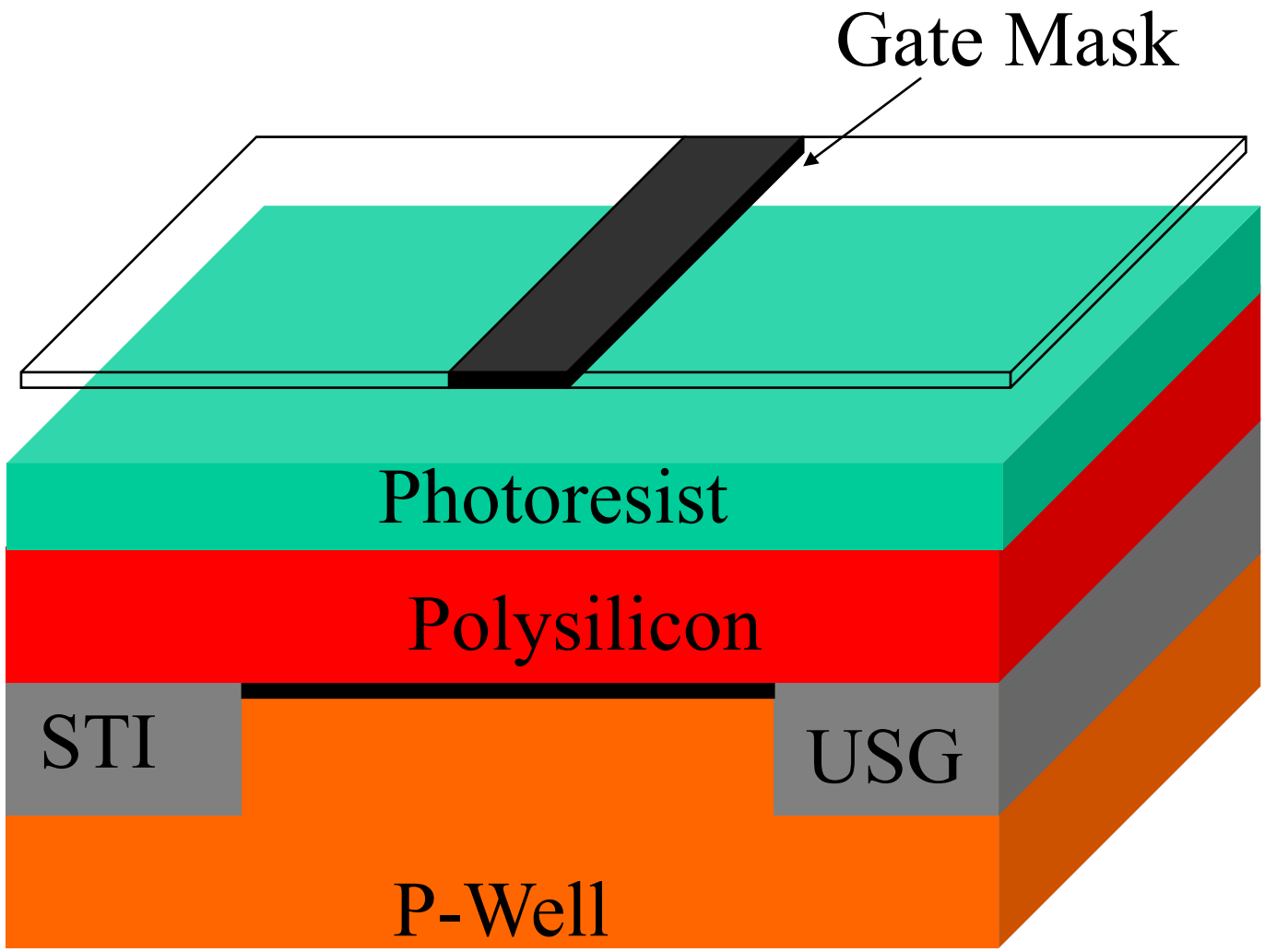
Photoresist Coating



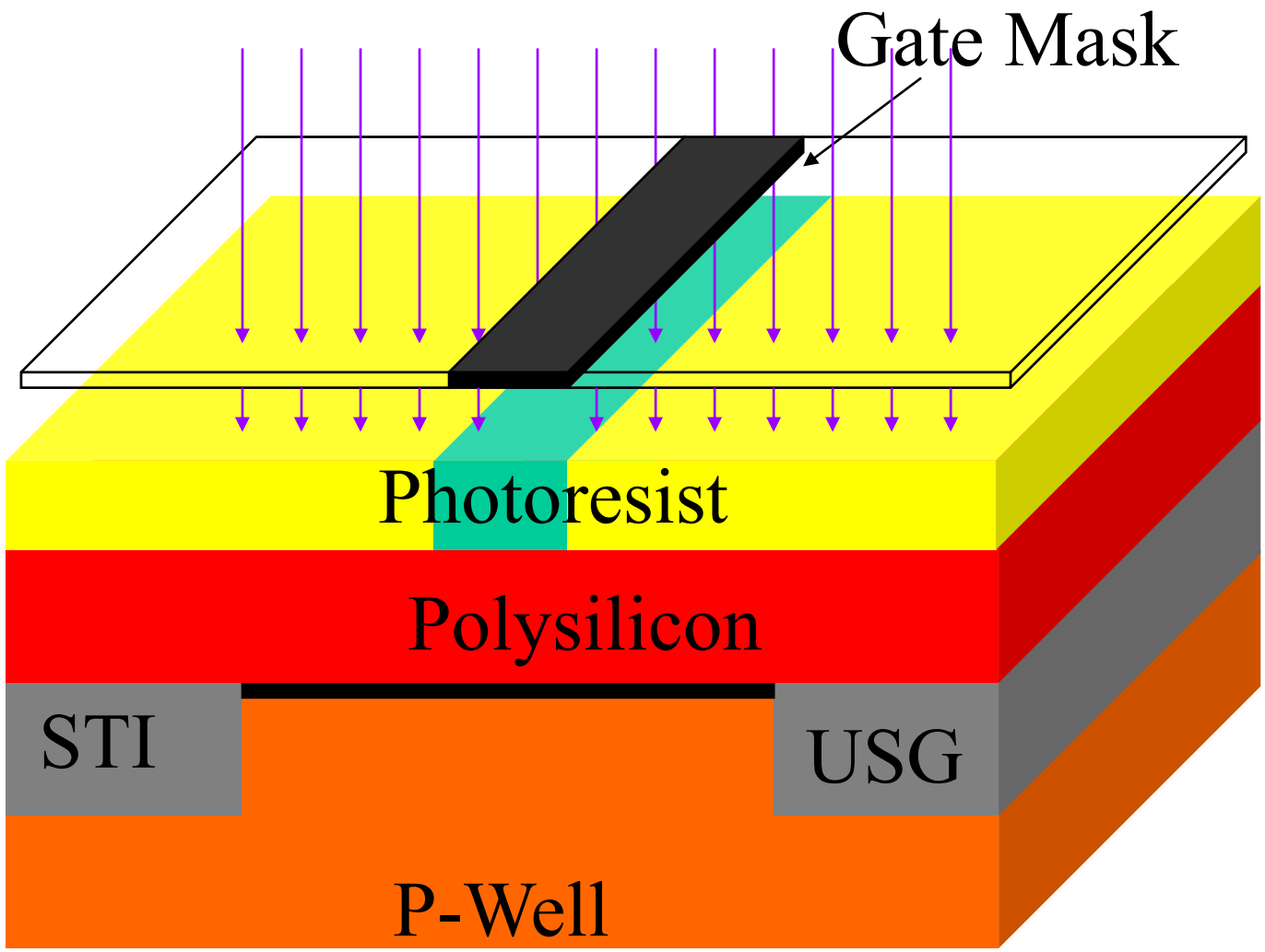
Soft Bake



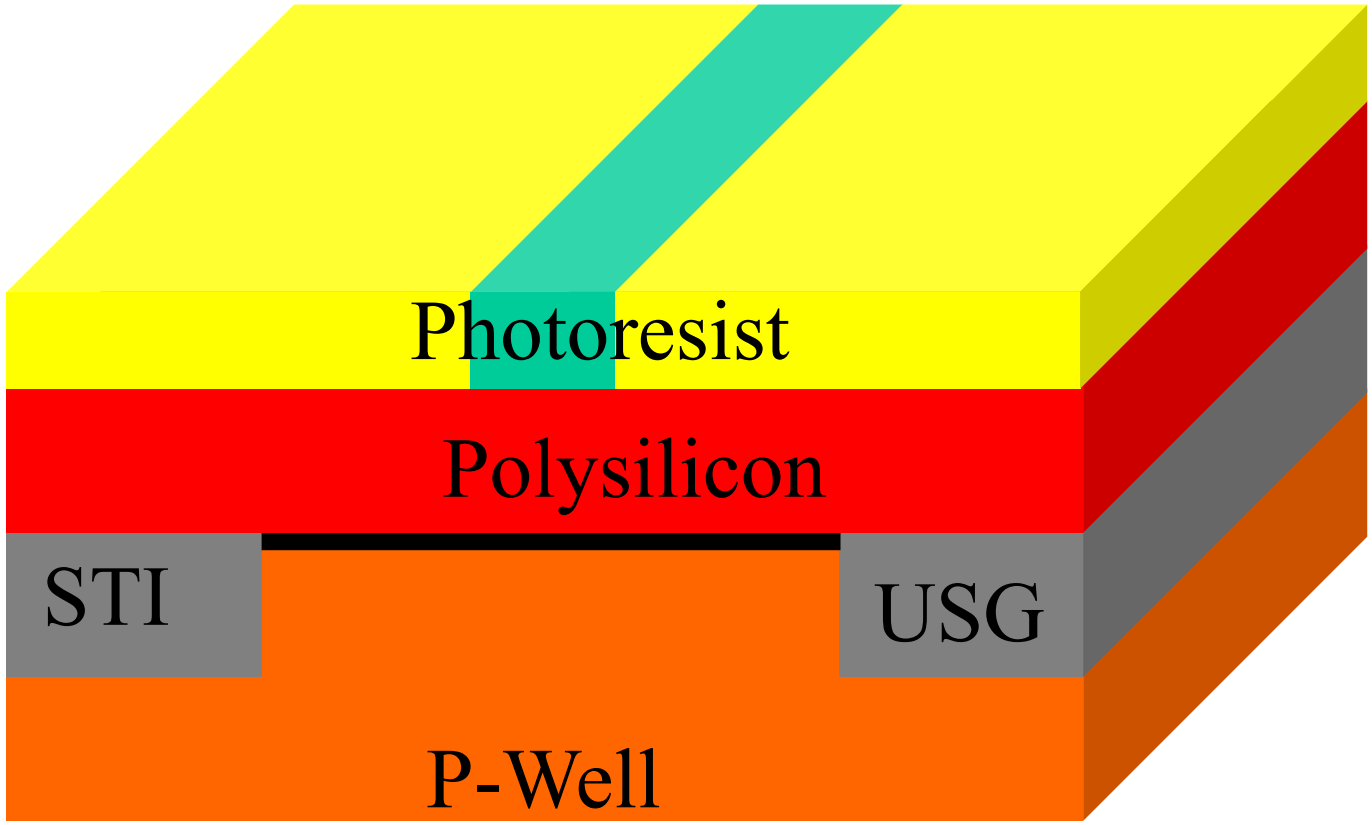
Alignment and Exposure



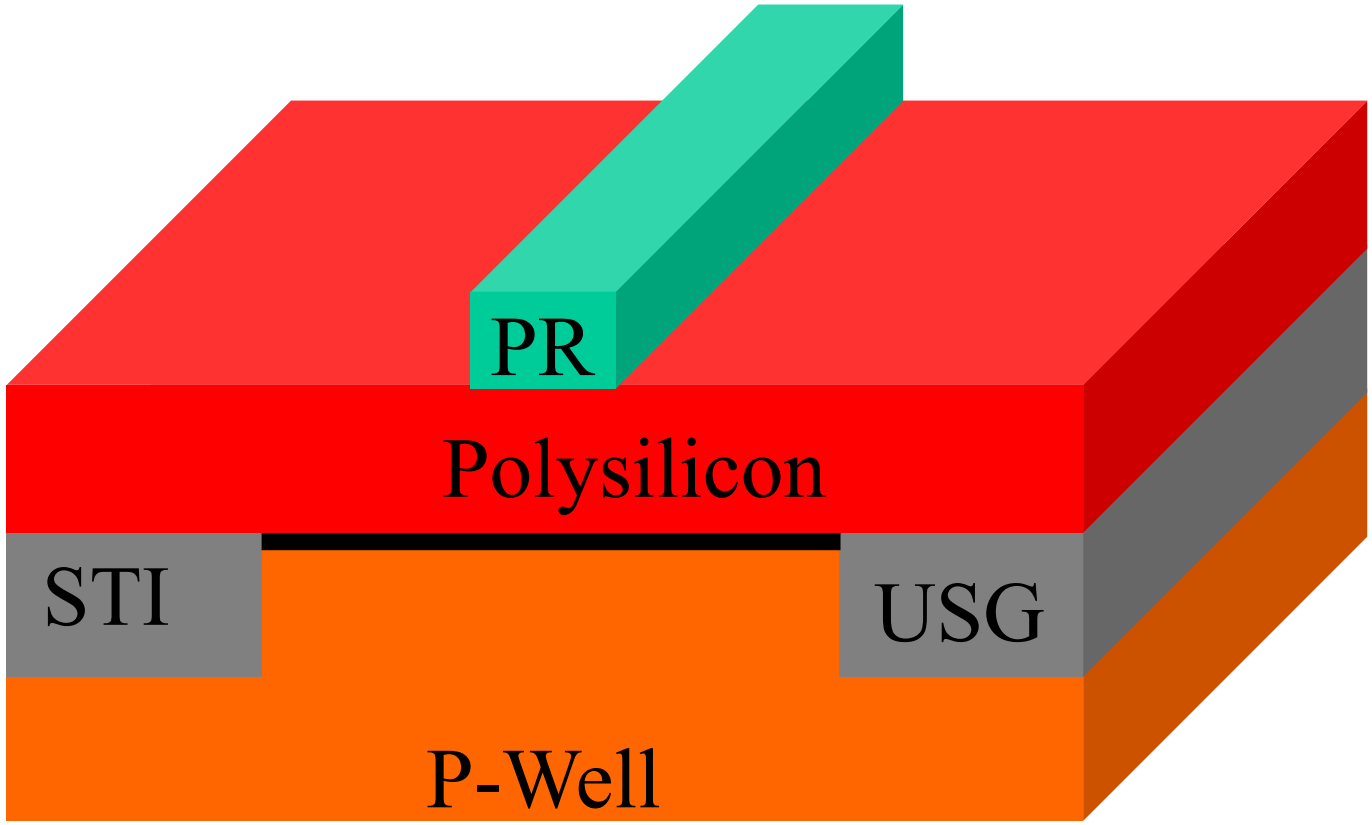
Alignment and Exposure



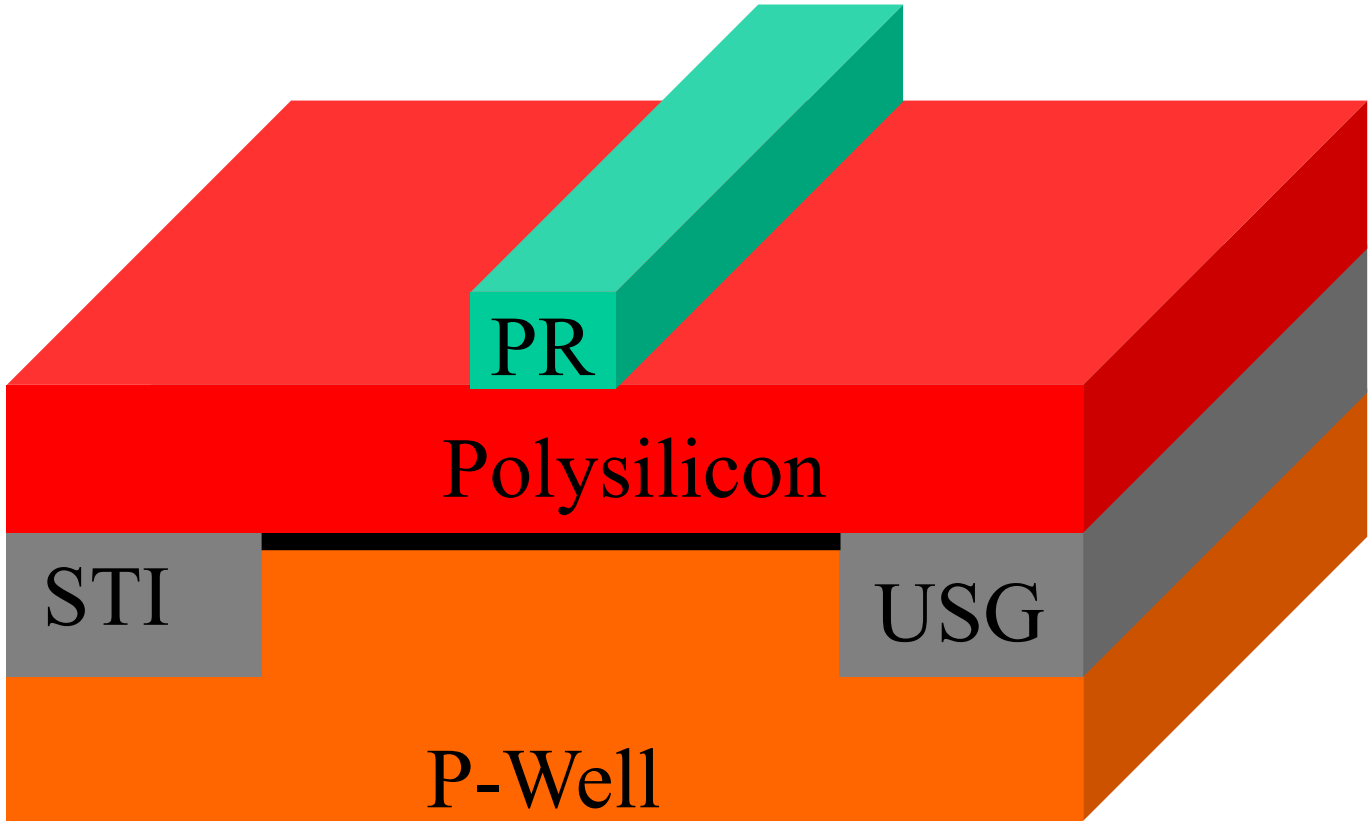
Post Exposure Bake



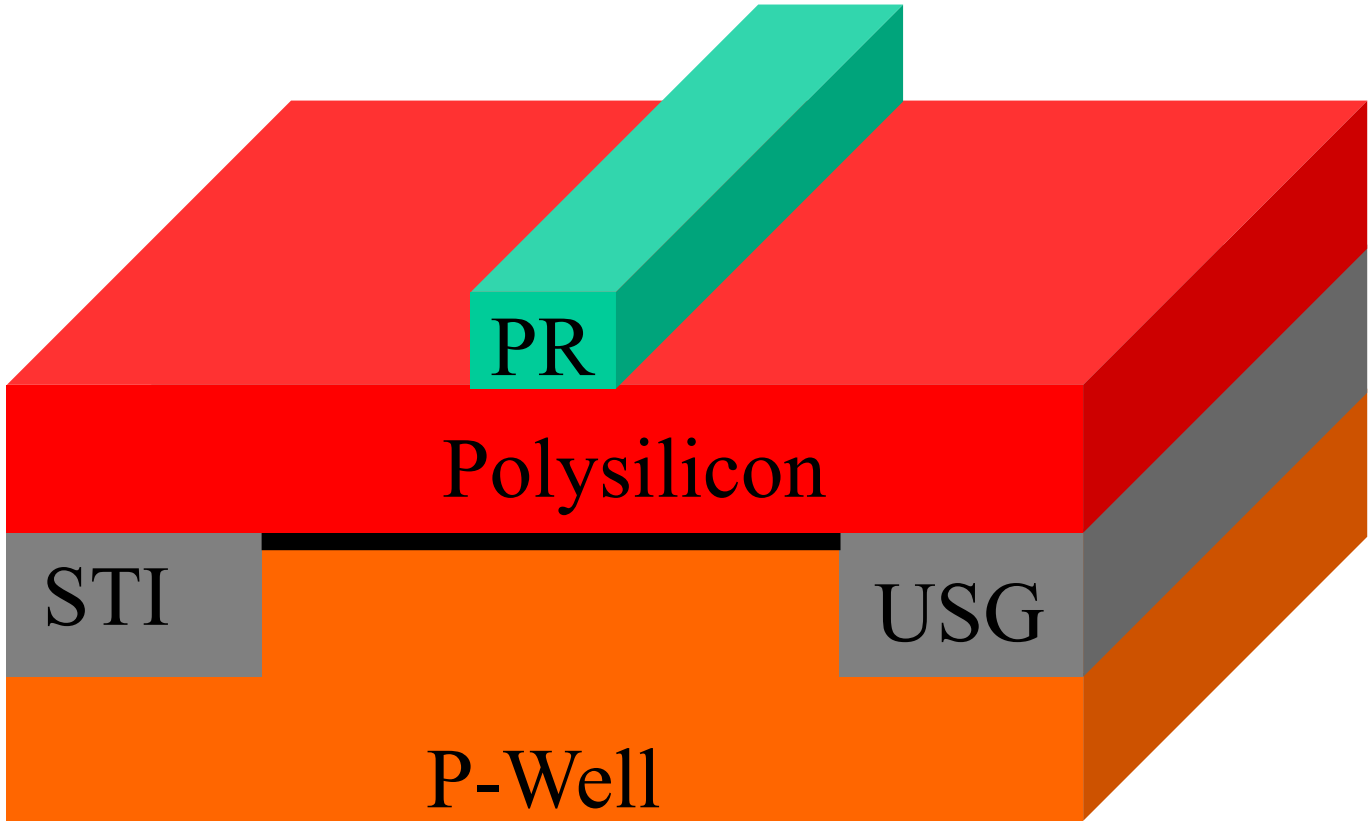
Development



Hard Bake



Pattern Inspection



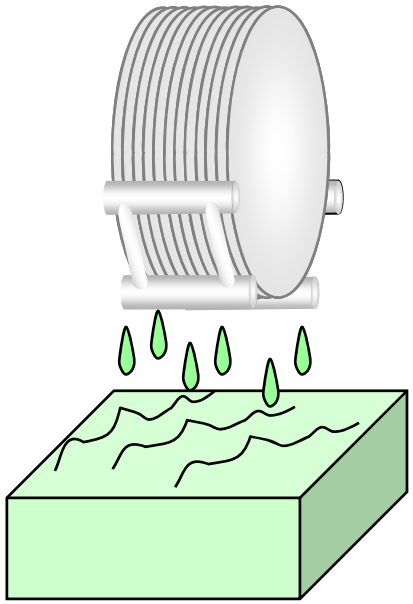
Wafer Clean

- 去除污染物
- 去除微粒
- 減少針孔和其他缺陷
- 改善光阻附著力
- 基本步驟
  - 化學清洗
  - 清洗
  - 旋乾

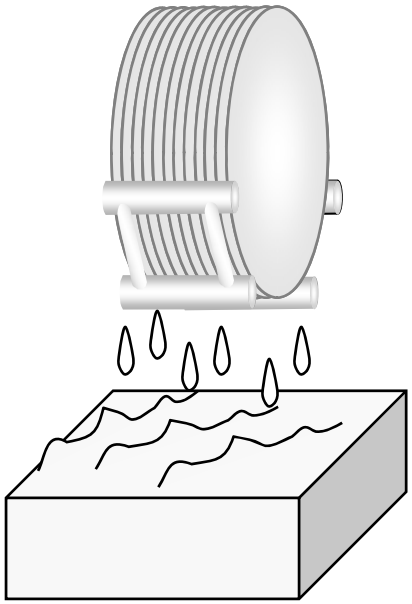
Photolithography Process, Clean

- 其他方式
  - 高壓氮氣吹離
  - 旋轉刷洗滌器
  - 高壓水流

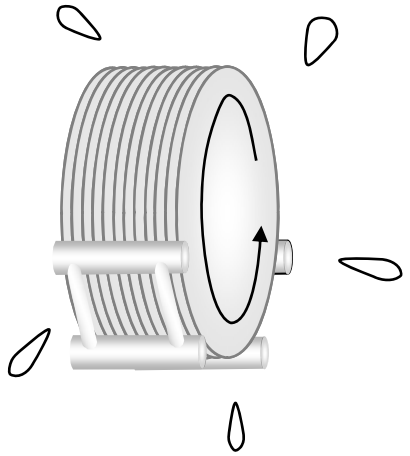
Wafer Clean Process



Chemical Clean



Rinse



Dry

Photolithography Process, Prebake

- 脫水烘烤(Dehydration bake)
- 去除晶圓表面上溼氣
- 在光阻和表面增加附著力
- 大約100 ℃
- 完成底漆層(primer)塗佈

Photolithography Process, Primer

- 增加光阻和晶圓表面的附著力
  - 常使用六甲基二戊烷(Hexamethyldisilazane ,HMDS)
- HMDS蒸發塗佈在光阻塗佈之前
  - 在預烘烤(pre-bake)製程中以臨場(in-situ)方式完成
  - 光阻塗佈前在冷卻平板上降低晶圓溫度

HMDS分子式

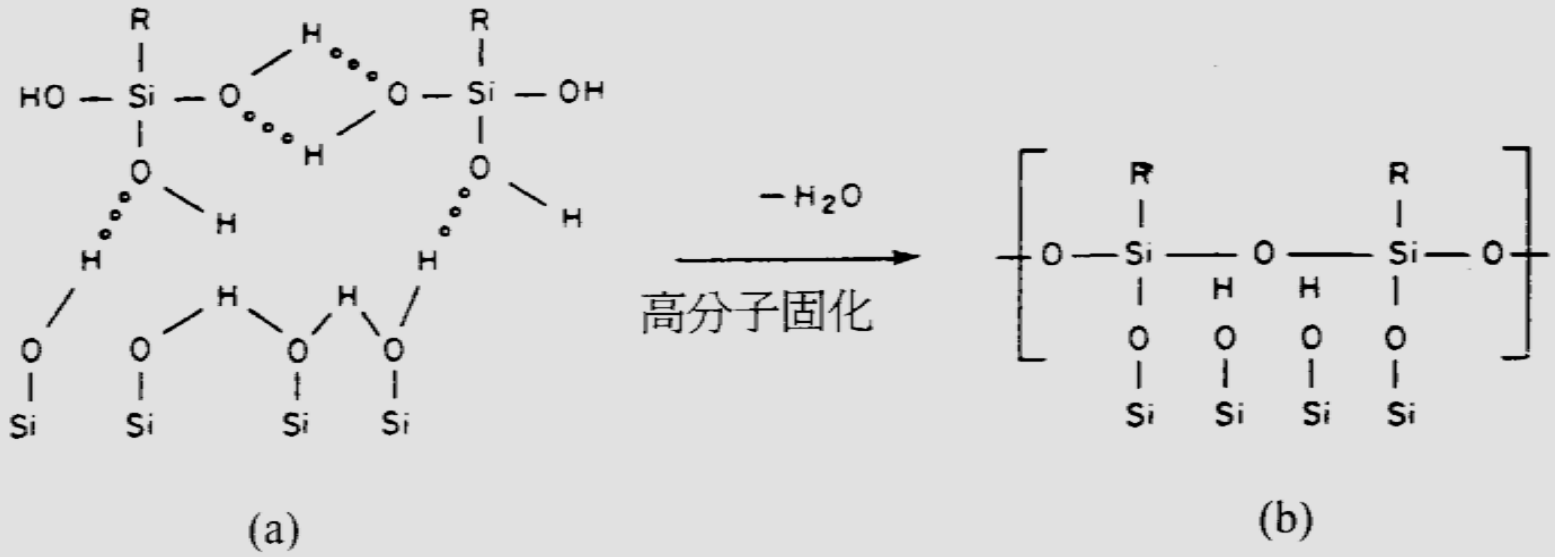
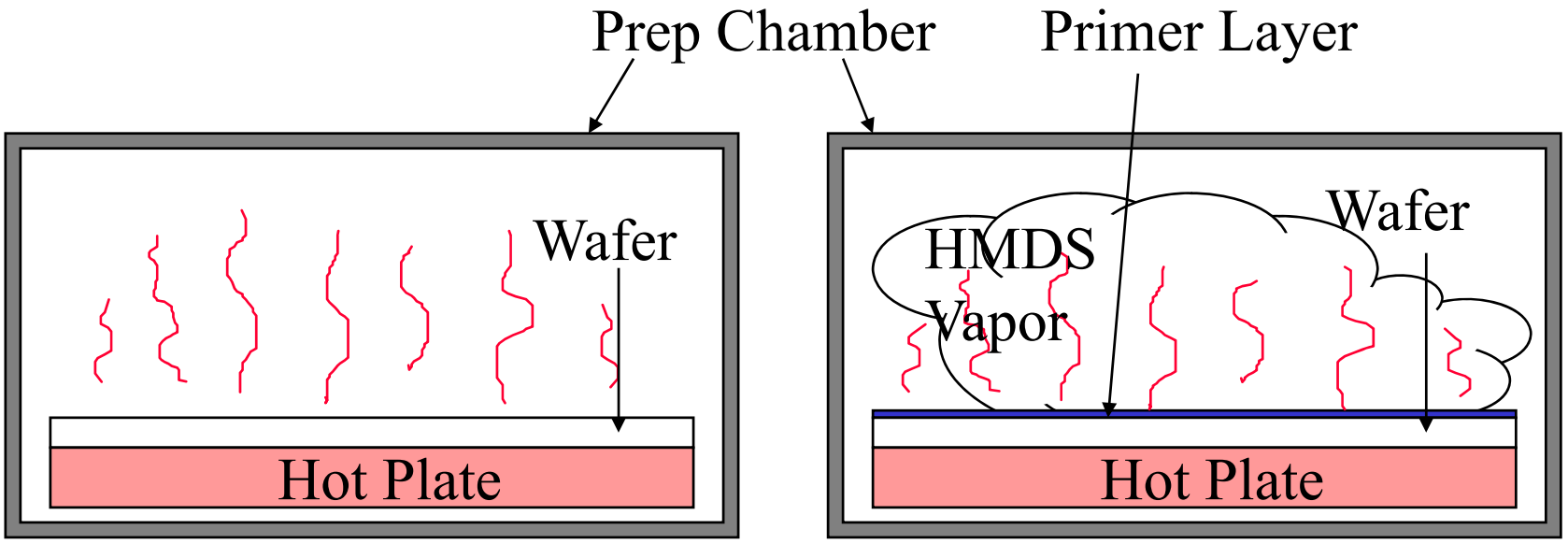


圖 7-3　顯示以HMDS 進行晶片的塗底時，晶片上的HMDS 在 (a) 塗底後與 (b) 固化後的化學結構[4]

Pre-bake and Primer Vapor Coating



Dehydration Bake

Primer Vapor Coating

Wafer Cooling

- 晶圓需要冷卻
- 晶圓冷卻平板
- 溫度會影響光阻黏性
  - 影響光阻自旋塗佈厚度

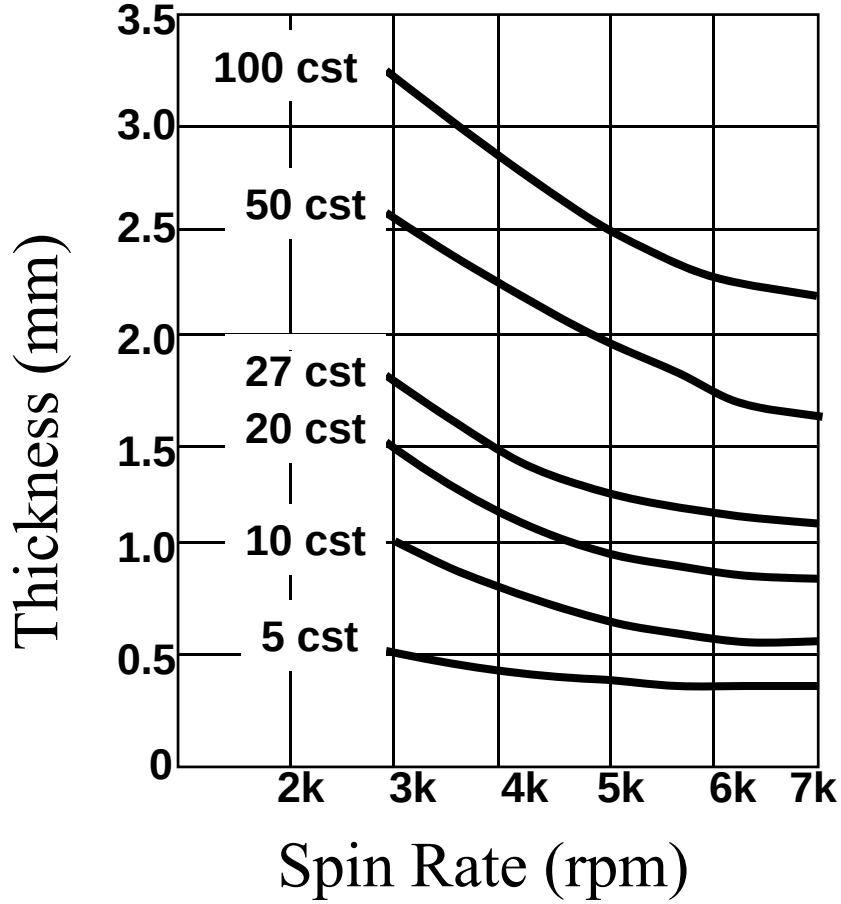
Spin Coating

- 晶圓放置在有真空吸盤(vacuum chuck的)轉軸上
- 高速旋轉
  - 將液體光阻鋪於晶圓中心
  - 光阻利用離心力(centrifugal force)散佈
  - 均勻塗佈在晶圓上

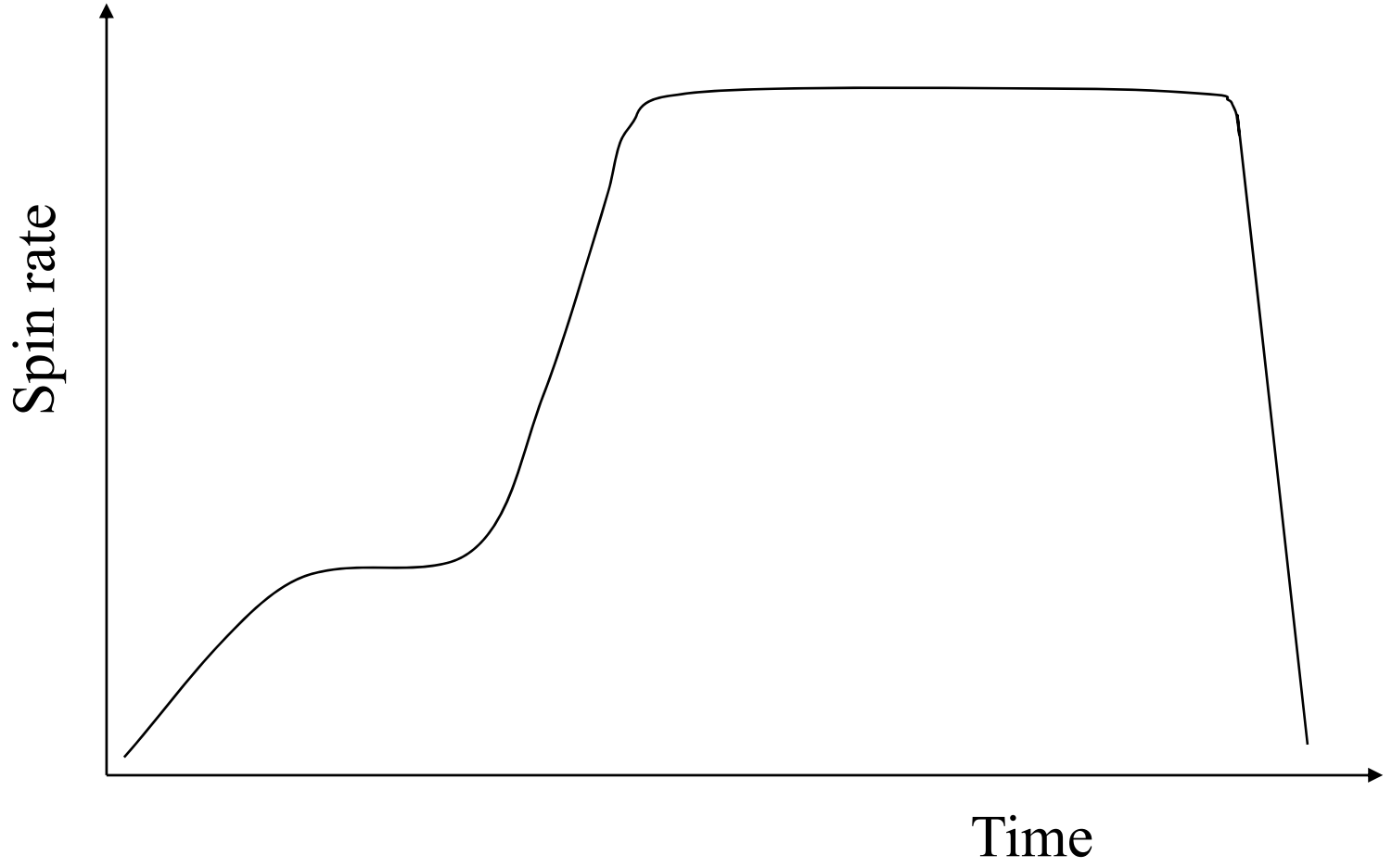
Viscosity

- 液體粘附在固體表面
- 在自旋塗佈影響光阻厚度
- 光阻型式和溫度皆會影響
- 需要高速旋轉以均勻塗佈

Relationship of Photoresist Thickness to Spin Rate and Viscosity



Dynamic Spin Rate



PR Spin Coater

光阻在旋轉的晶圓表面散佈

晶圓固定在真空吸盤(vacuum chuck)上

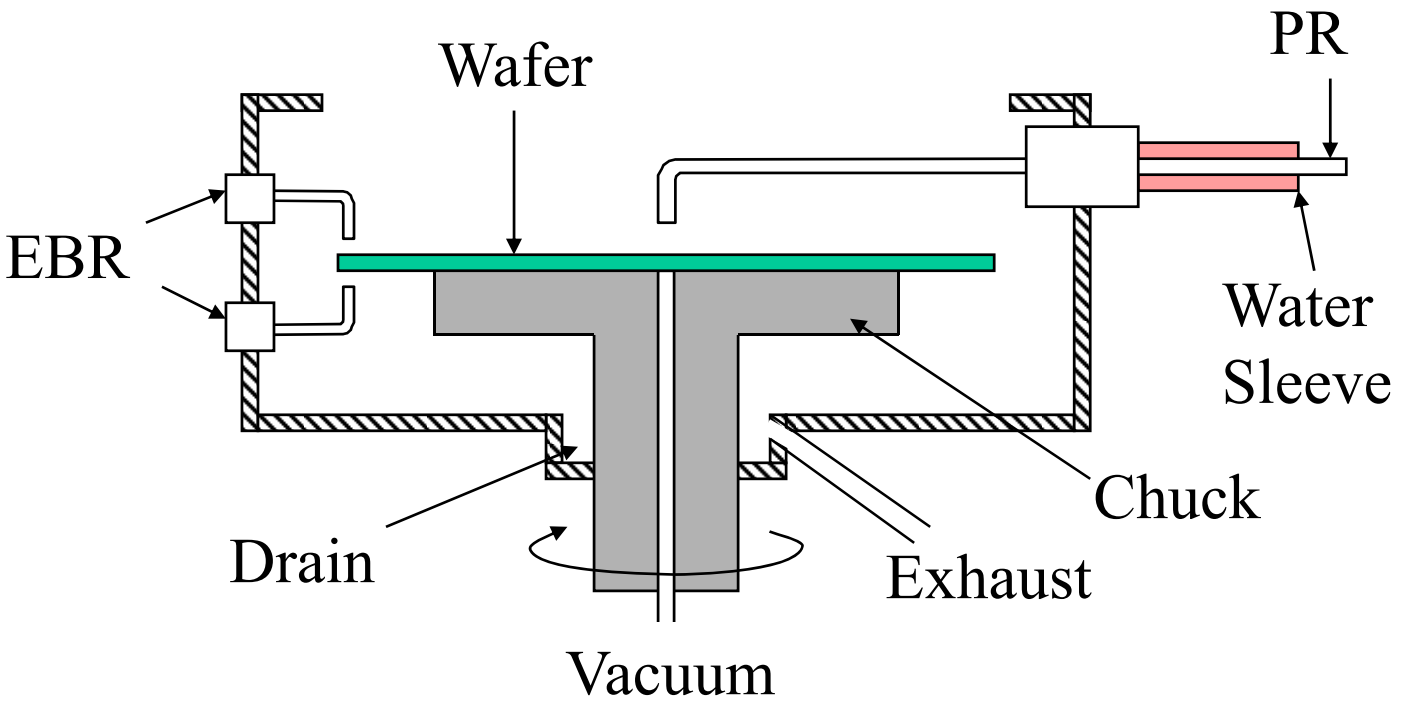
低速自旋轉動~ 500 rpm

加速至 ~ 3000 - 7000 rpm

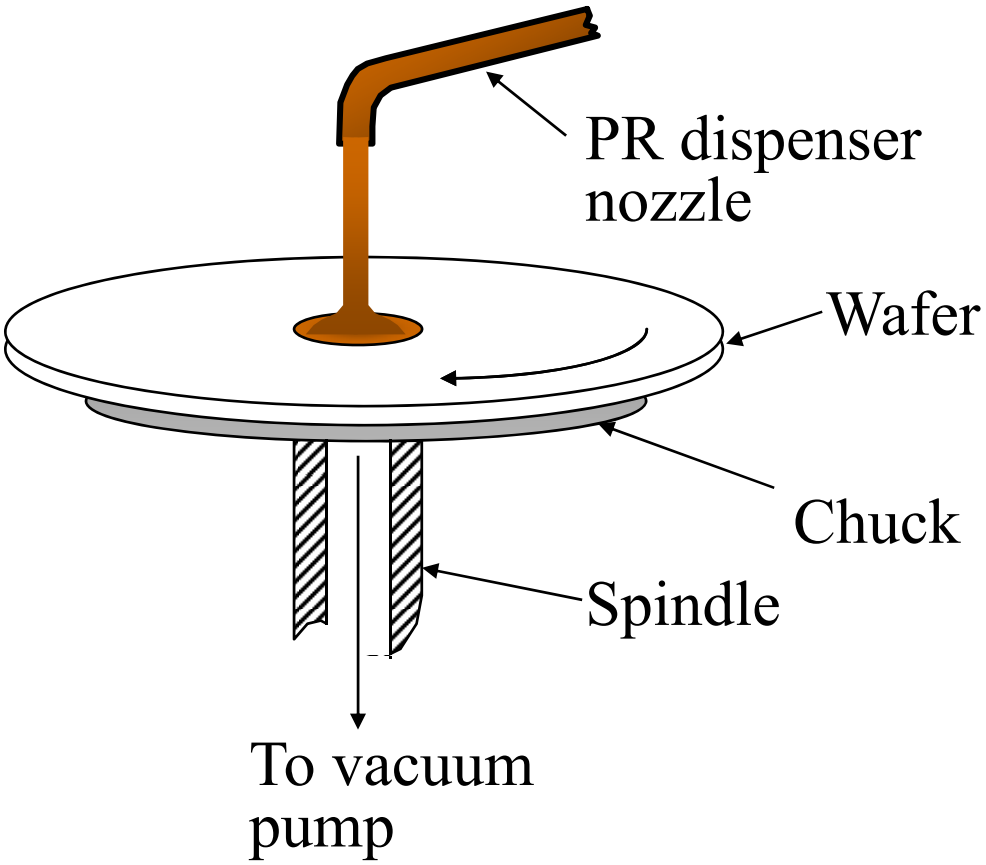
Spin Coater

- 從軌道系統的機械人到自動裝載晶圓系統
- 真空吸盤固定晶圓
- 溶液收集再排出
- 排器的特點
- 可控制的旋轉馬達
- Dispenser and dispenser pump
- 邊緣球狀物移除法(Edge bead removal,EBR)

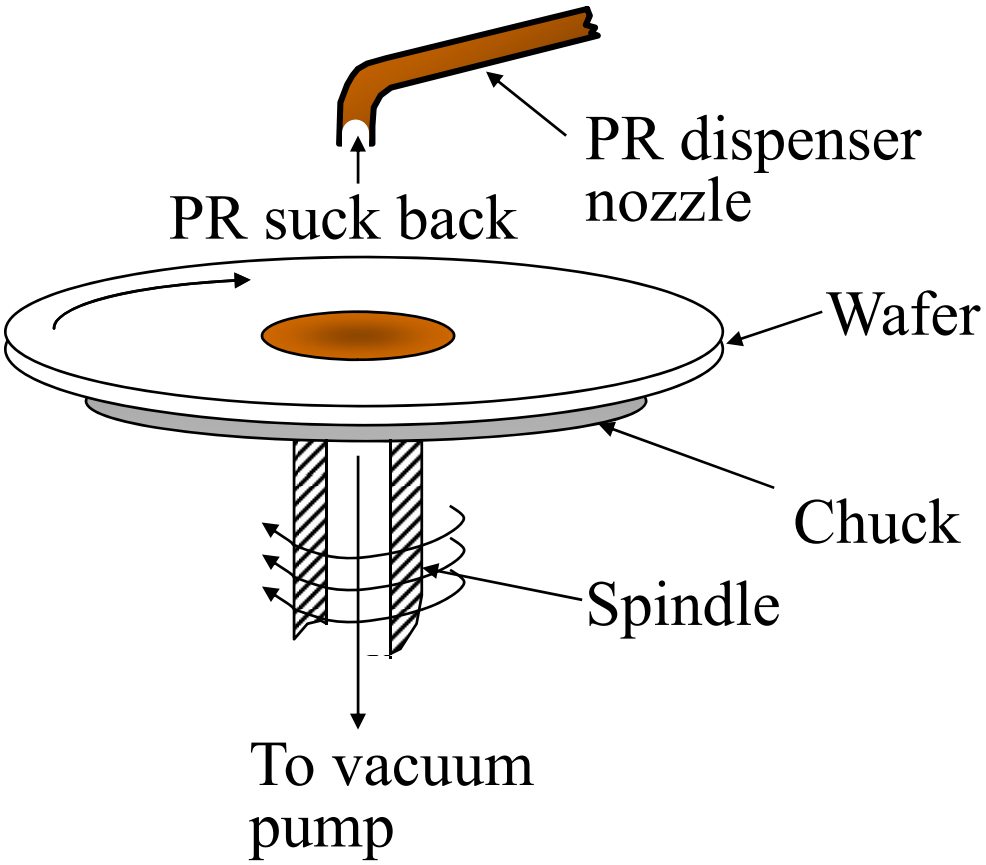
Photoresist Spin Coater



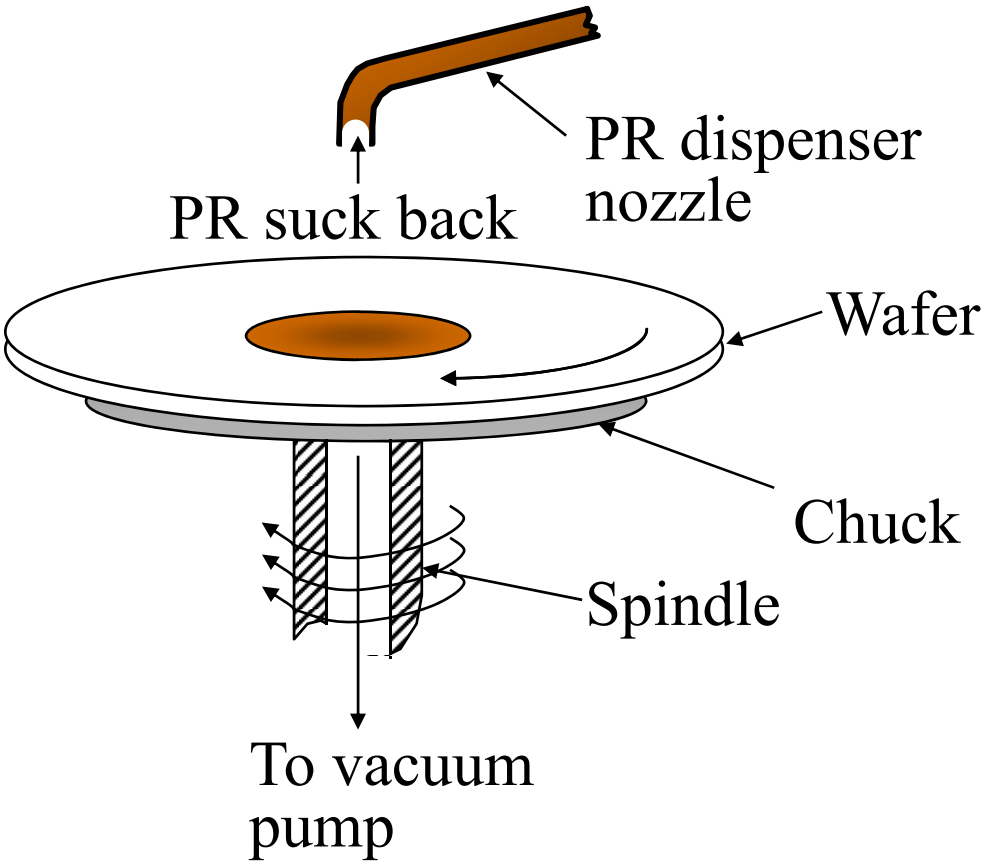
Photoresist Applying



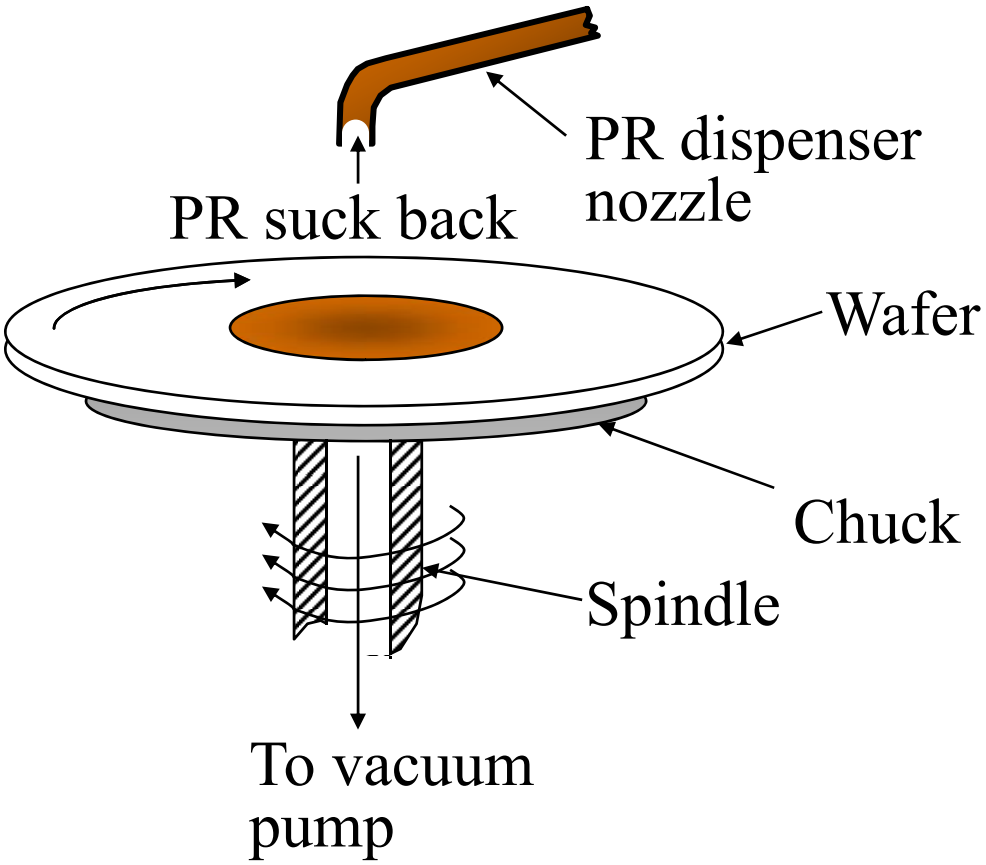
Photoresist Suck Back



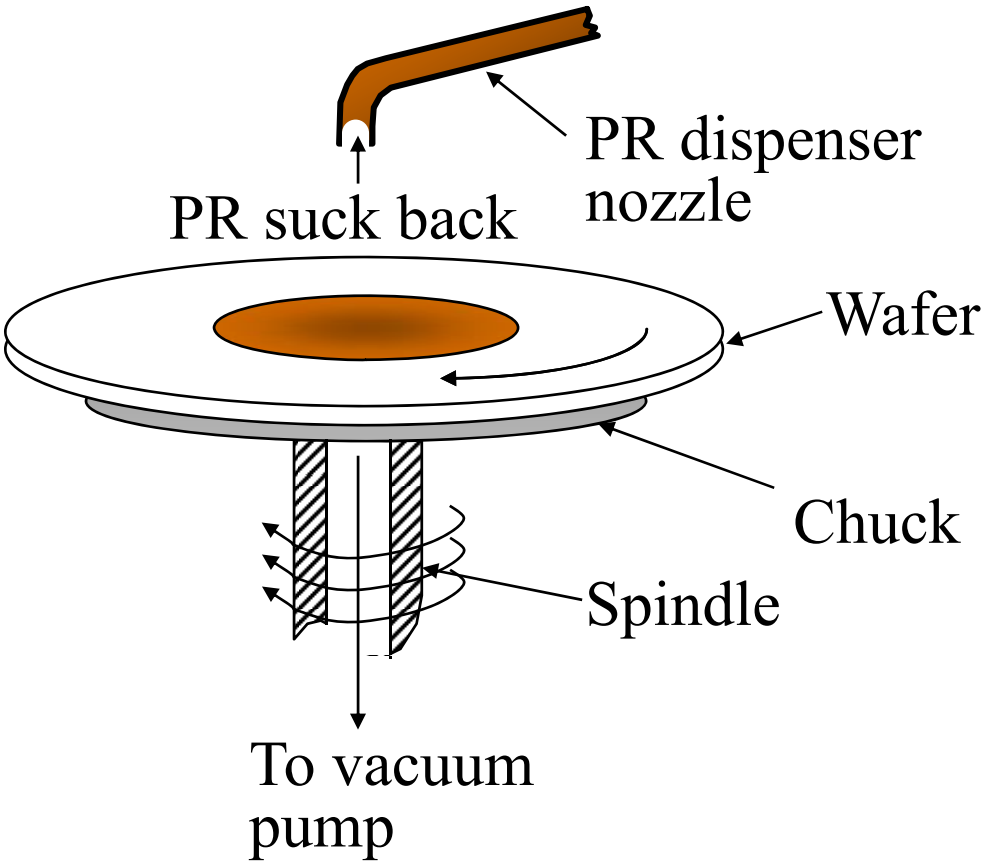
Photoresist Spin Coating



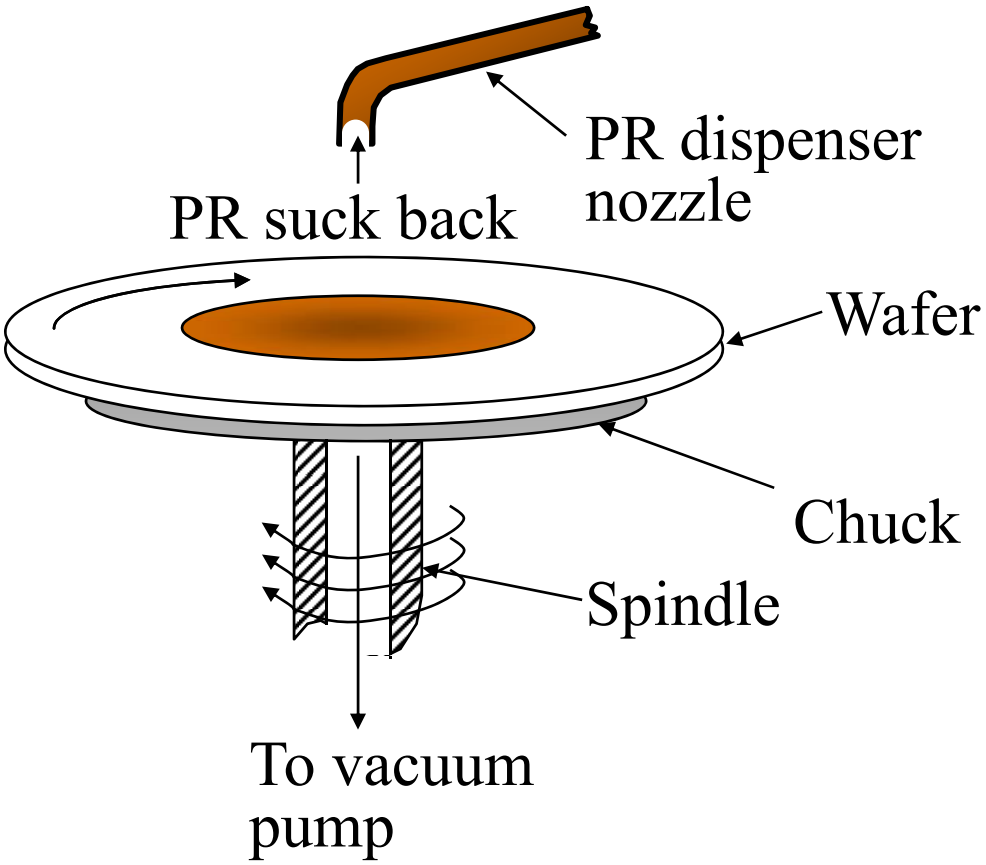
Photoresist Spin Coating



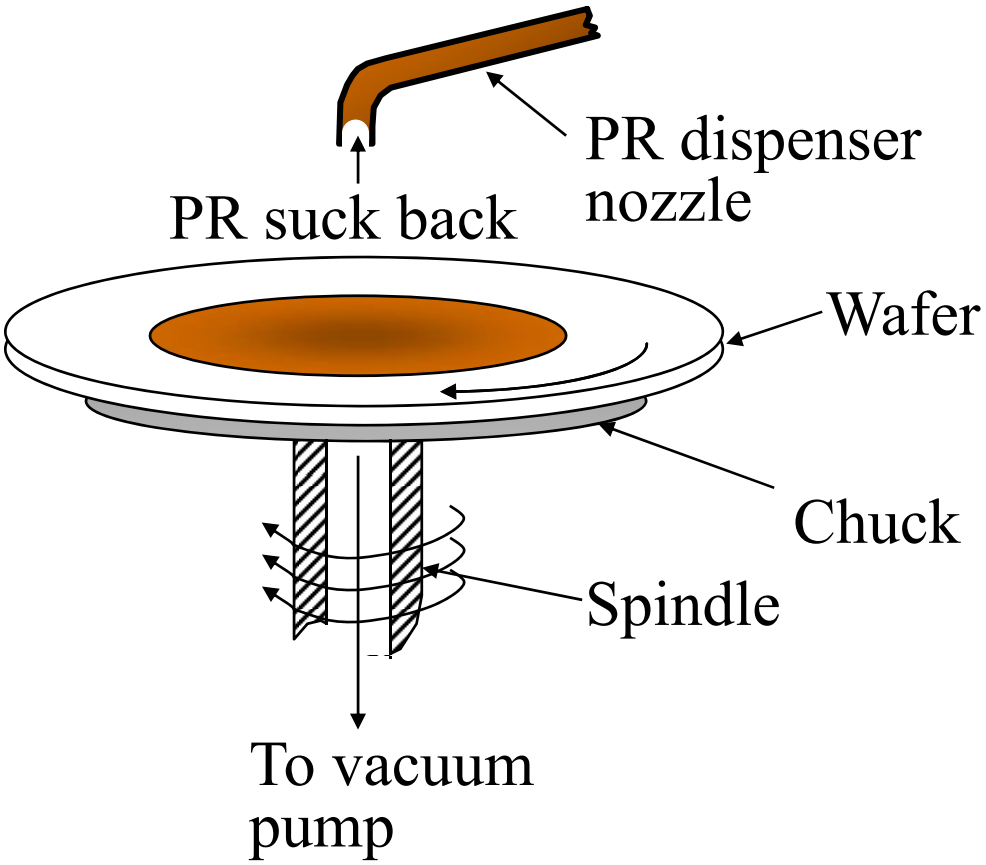
Photoresist Spin Coating



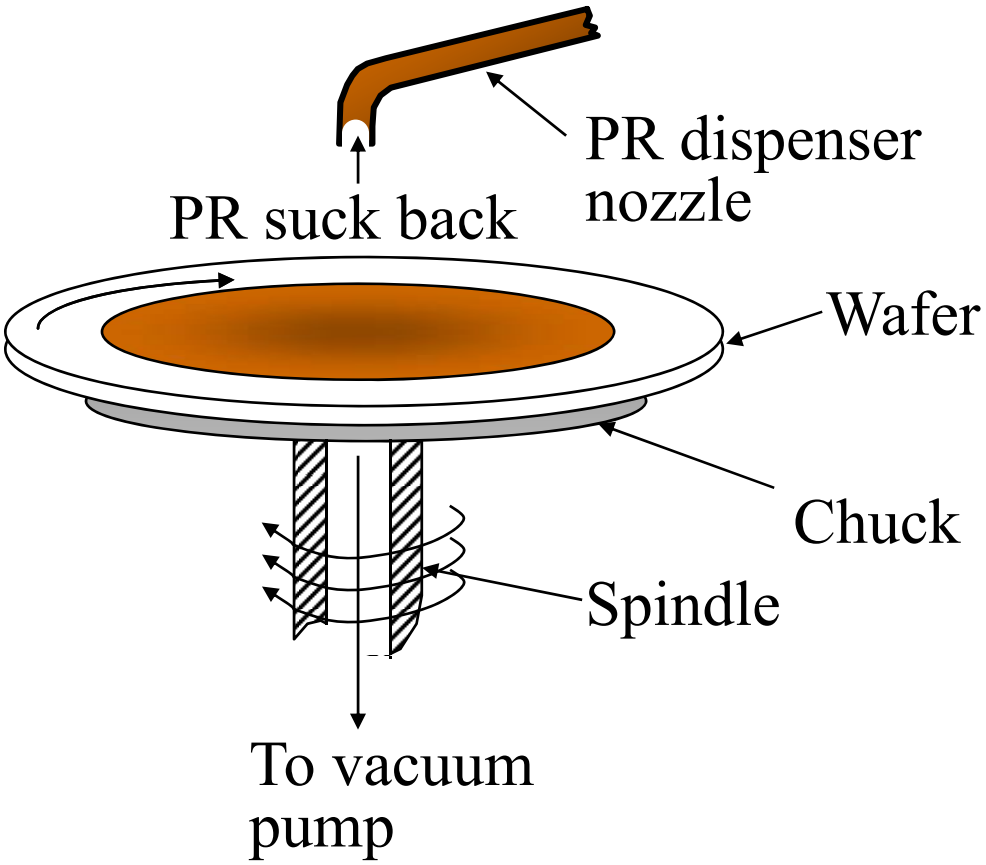
Photoresist Spin Coating



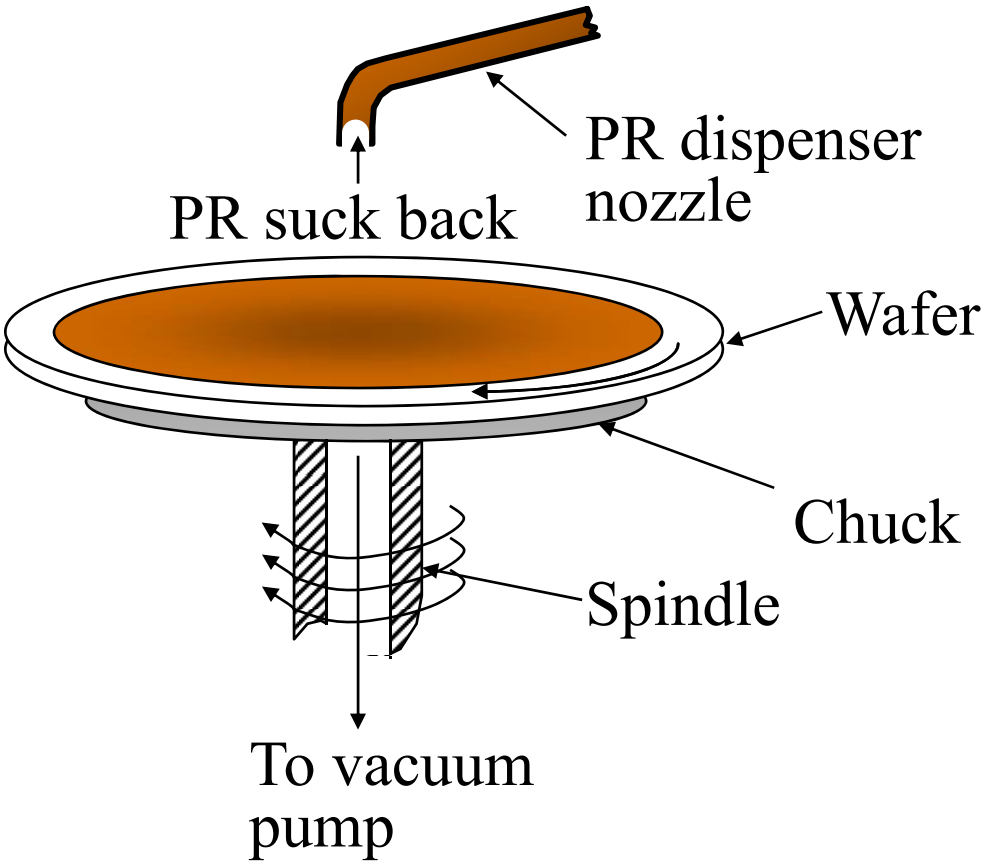
Photoresist Spin Coating



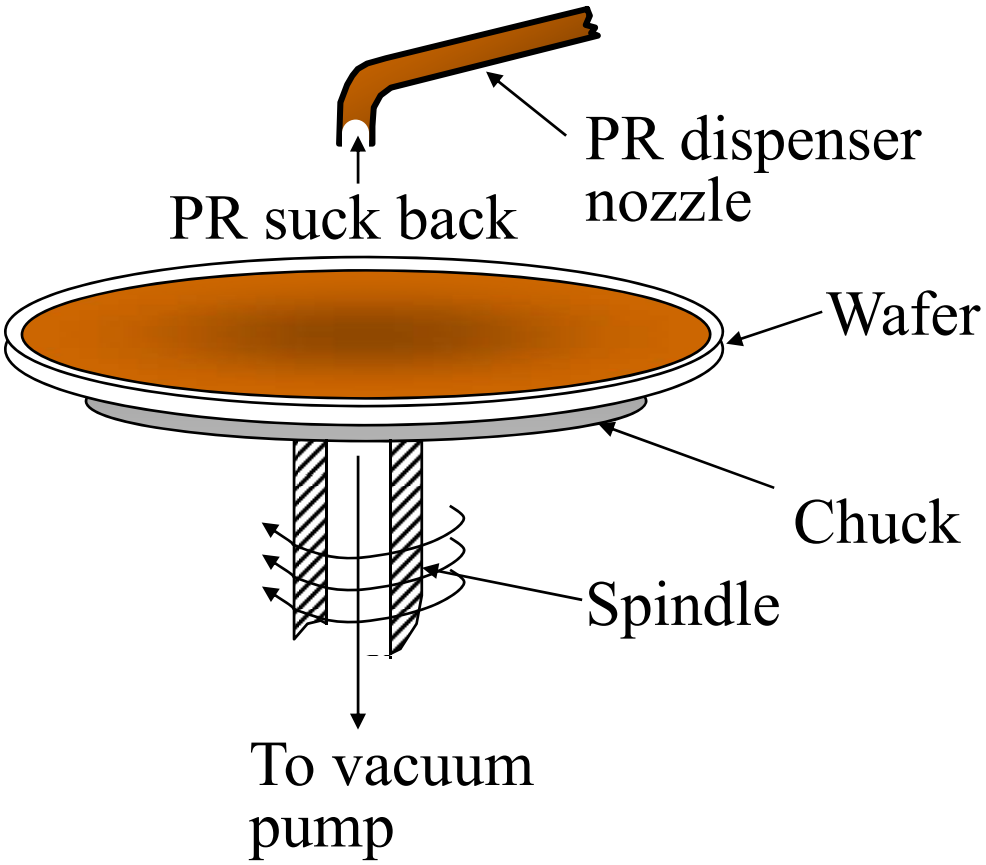
Photoresist Spin Coating



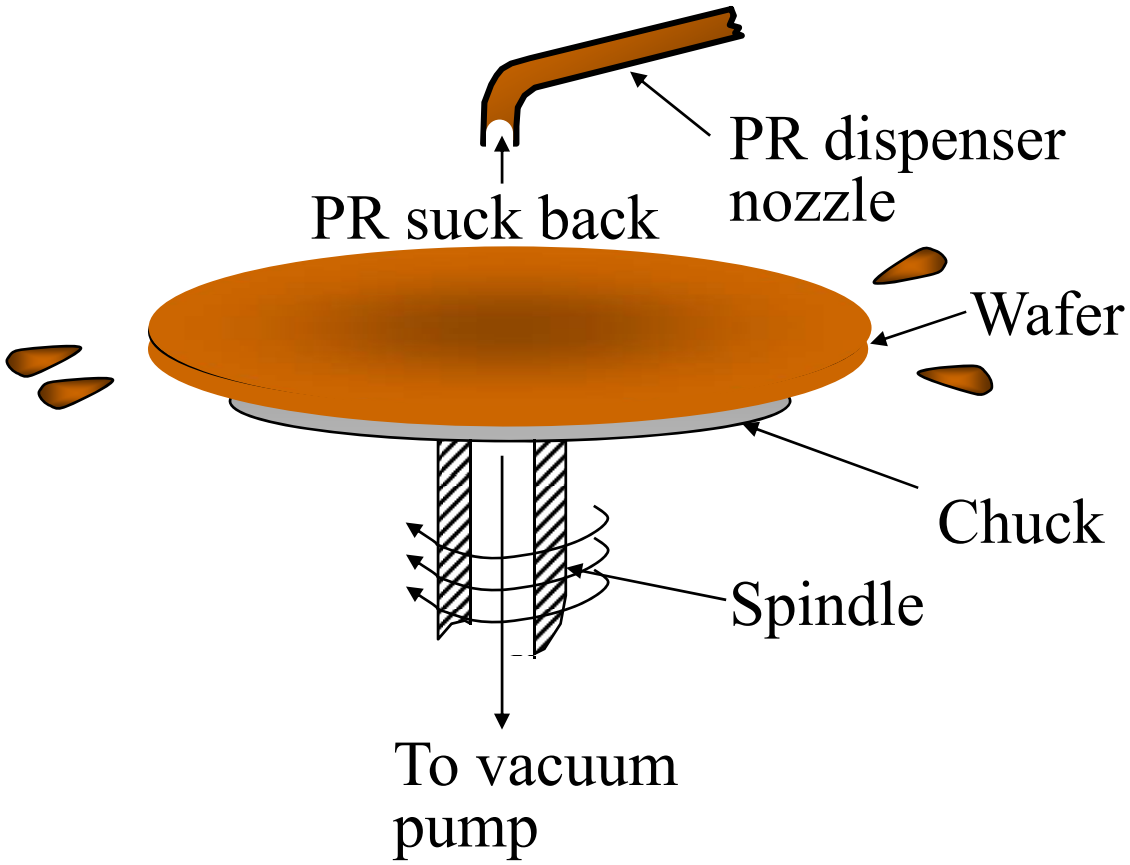
Photoresist Spin Coating



Photoresist Spin Coating



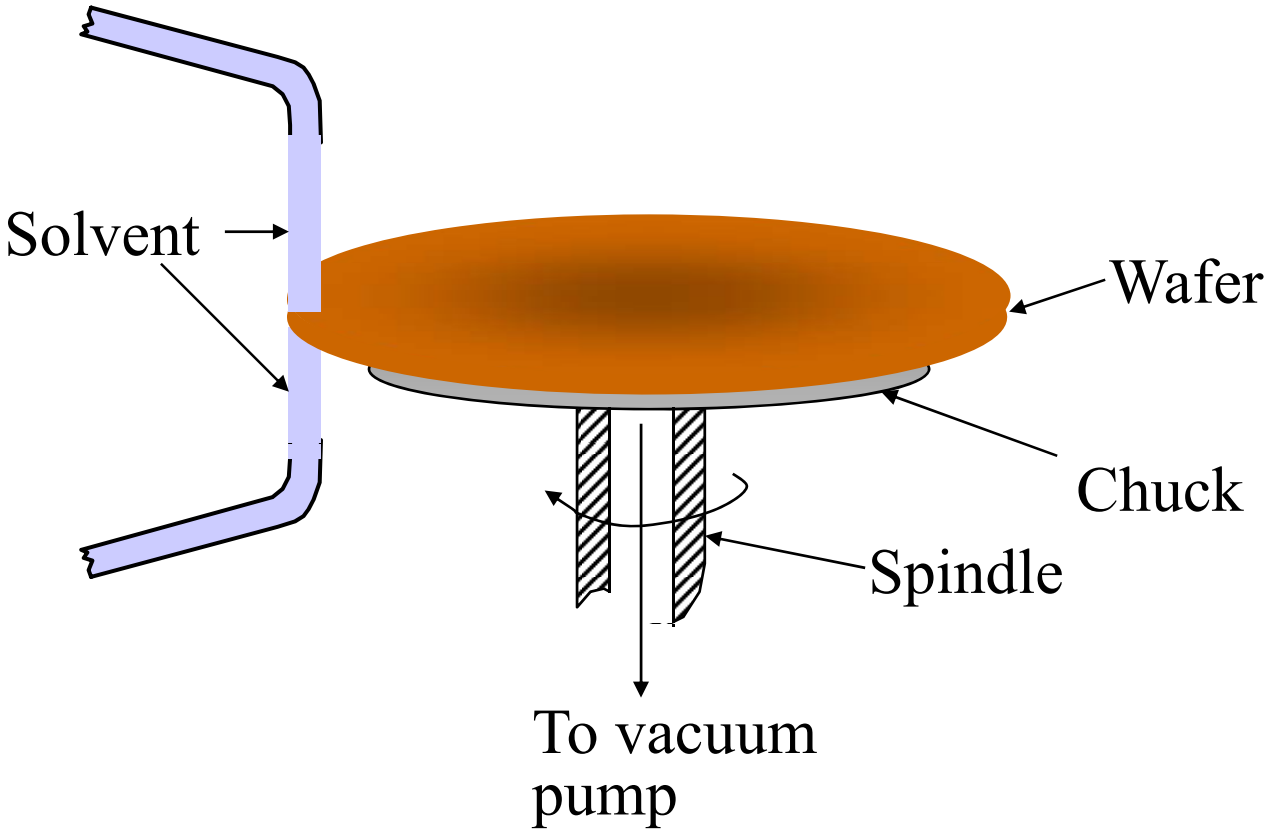
Photoresist Spin Coating



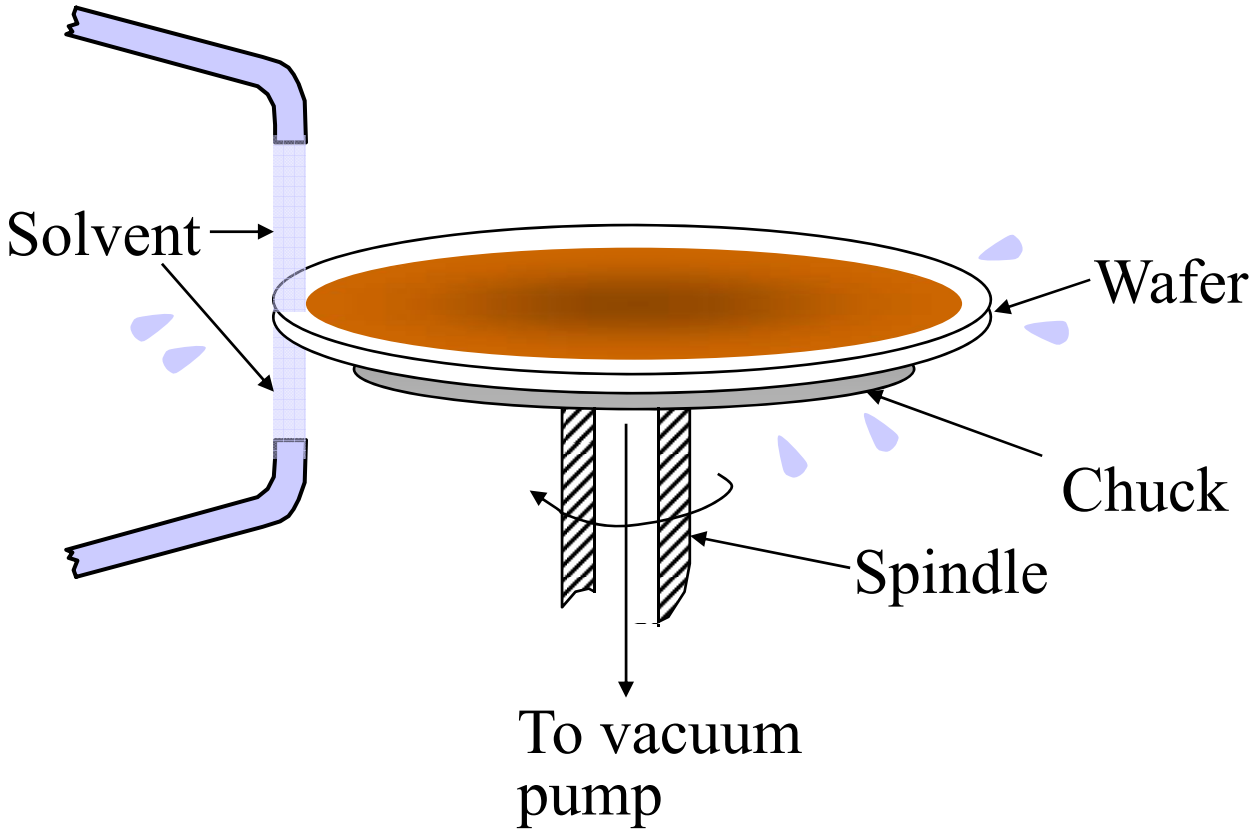
Edge Bead Removal (EBR)

- 光阻擴散到邊緣及後方
- 在機械式處理中光阻會剝落而造成微粒
- 化學方式的邊緣球狀物移除法
- 光學式的邊緣球狀物移除法

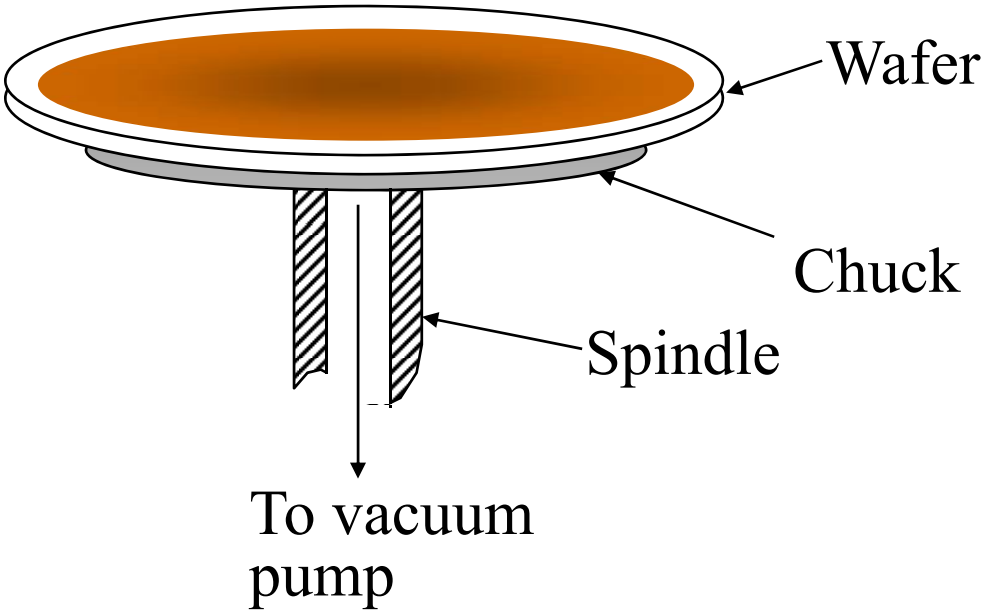
Edge Bead Removal



Edge Bead Removal



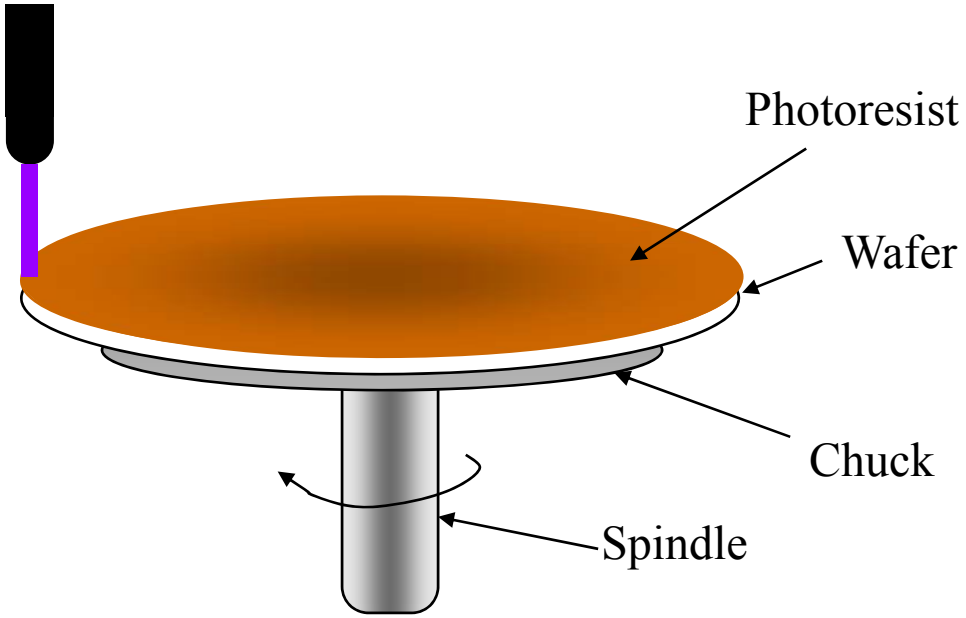
Ready For Soft Bake



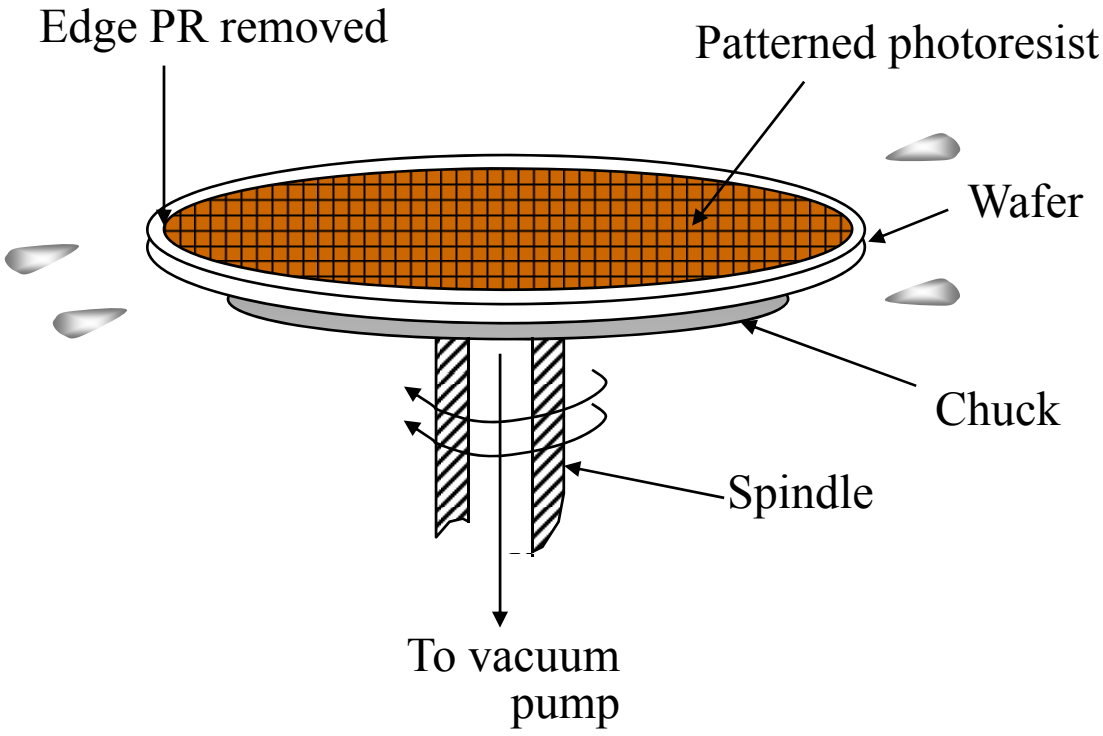
Optical Edge Bead Removal

- 在對準和曝光之後
  - 晶圓邊緣曝光Wafer edge expose (WEE)
  - 在顯影製程中邊緣的曝光光阻被溶解

Optical Edge Bead Removal



Developer Spin Off



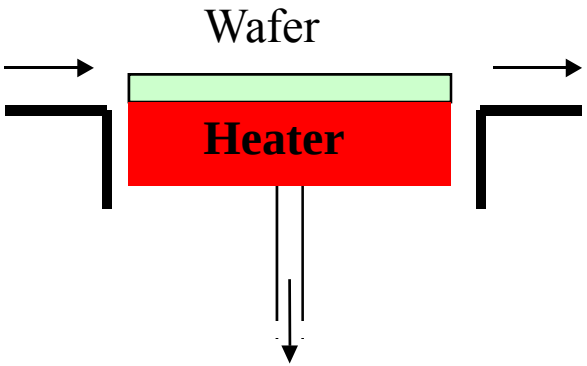
Soft Bake

- 蒸發光阻內部大部分的溶劑
- 溶劑有助製造薄光阻但吸收輻射並影響附著力
- 軟烘烤的溫度和時間依特定製程改變
- 過度烘烤(0ver bake)：使光阻聚合,曝光不靈敏
- 烘烤不足(Under bake)：影響附著力和曝光

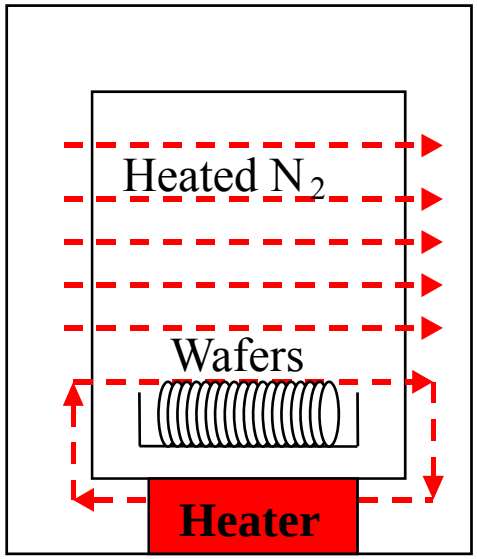
Soft Bake

- **加熱平板(Hot plates)**
- 對流恆溫烤箱(Convection oven)
- 紅外線烤箱(Infrared oven)
- 微波烤箱(Microwave oven)

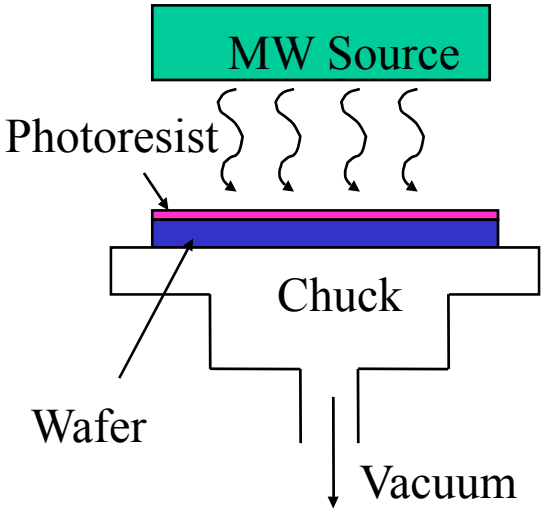
Baking Systems



Hot plate



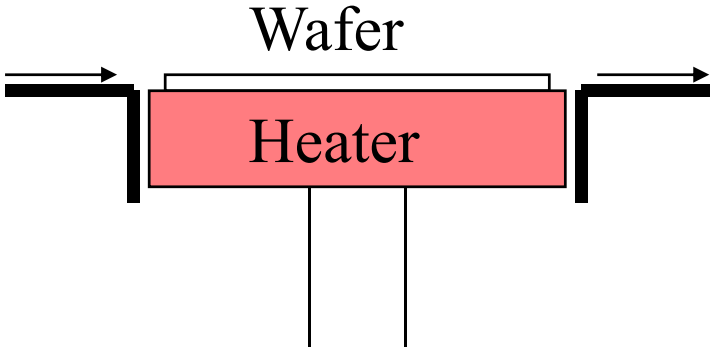
Convection oven



Microwave oven

Hot Plates

- 在工業上普遍被使用
  - 從底部加熱, 無硬外殼 “crust”
- 容易整合於晶圓軌道系統



Wafer Cooling

- 必須冷卻週遭的溫度
- 晶圓冷卻平板
  - 矽熱傳導係數： $2.5\times10^{-6}/°C$
  - 對於8英吋(200 mm)晶圓, 1 ℃的溫差產生0.5 μm的差距

Alignment and Exposure

- IC製程中最關鍵的過程
- IC製程中最昂貴的設備(步進機stepper)
- 最具挑戰性的技術
- 決定最小的晶圓尺寸
  - 從0.18 mm然後推至0.13 μm

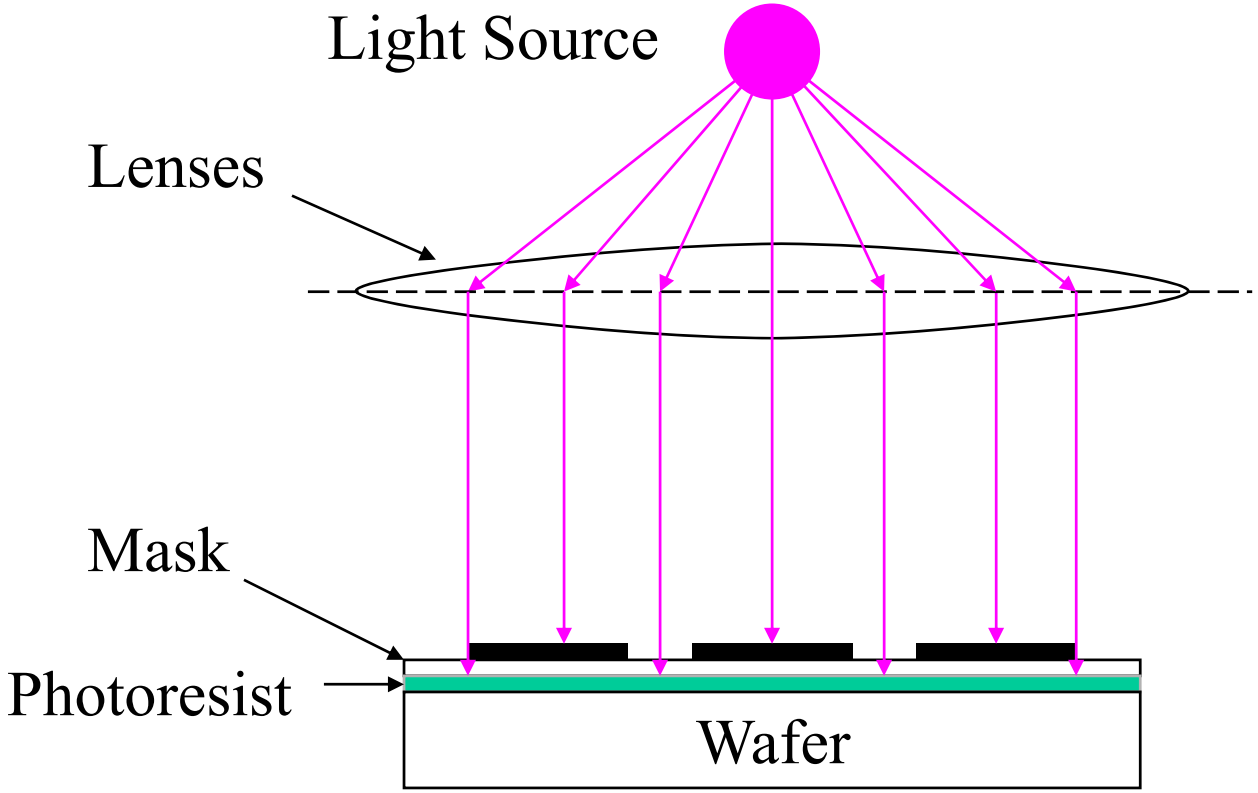
Alignment and Exposure Tools

- 接觸式印像機(Contact printer)
- 鄰接式印像機(Proximity printer)
- 投影式印像機(Projection printer)
- 步進機(Stepper)

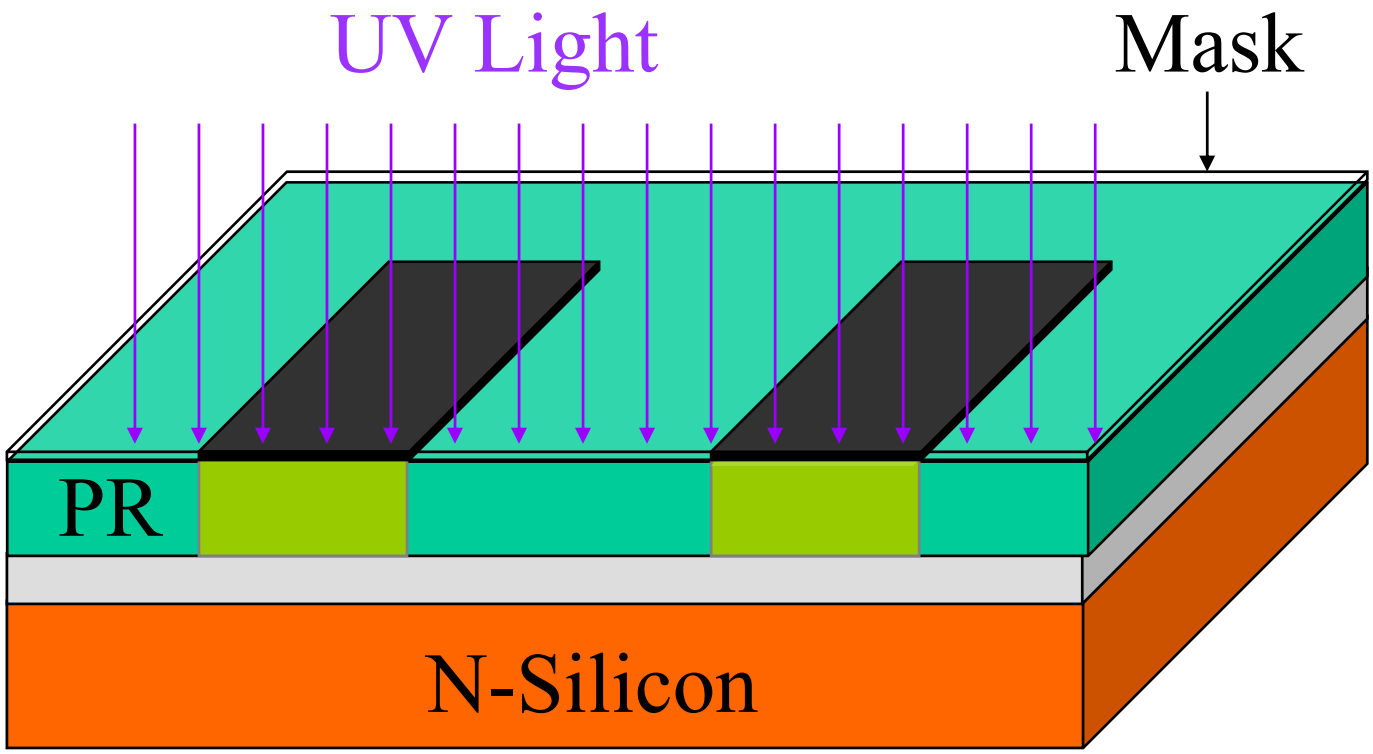
Contact Printer

- 簡單的設備
- 70年代中期前被使用
- 解析度：次微米
- 光罩與晶圓直接接觸,限制光罩的壽命
- 產生微粒

Contact Printer



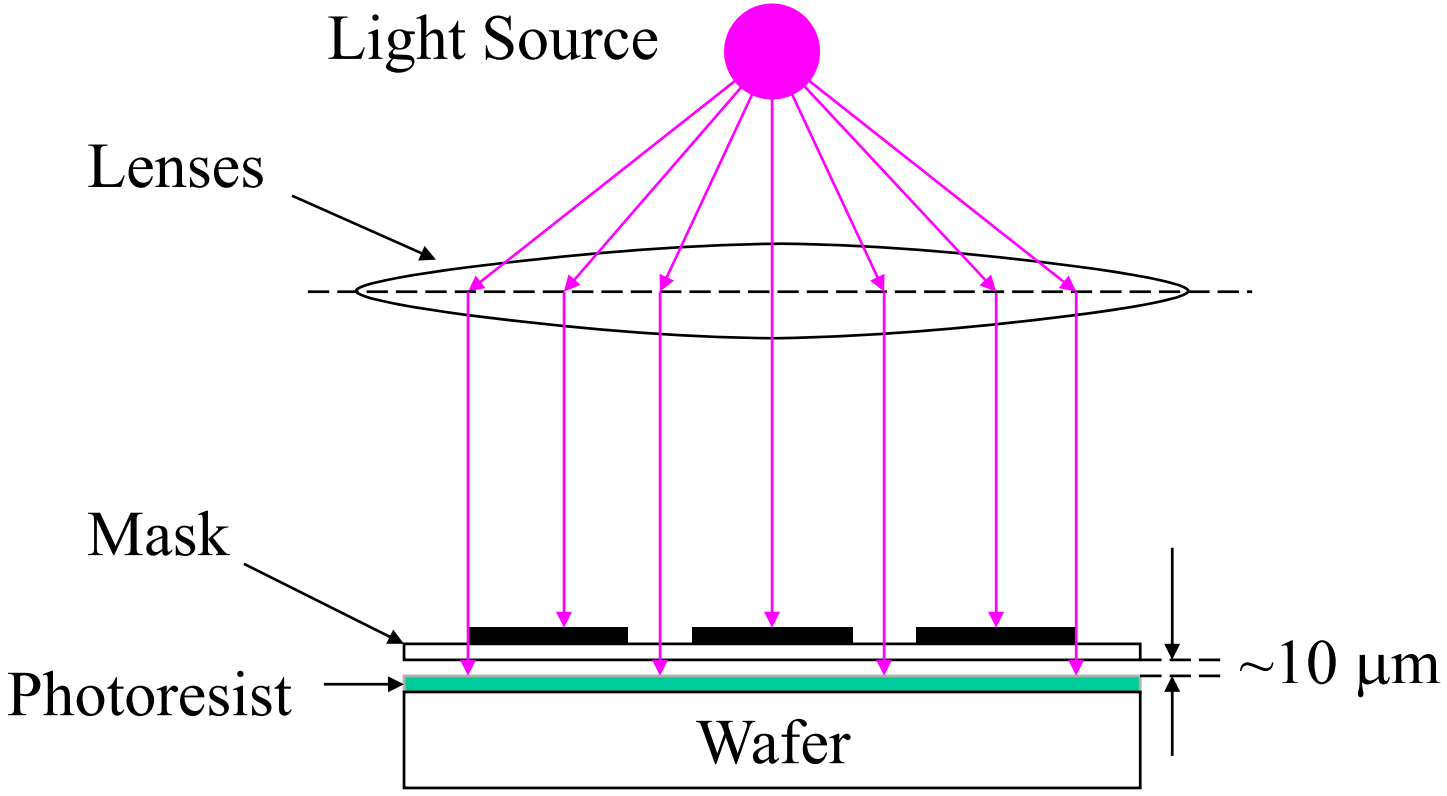
Contact Printing



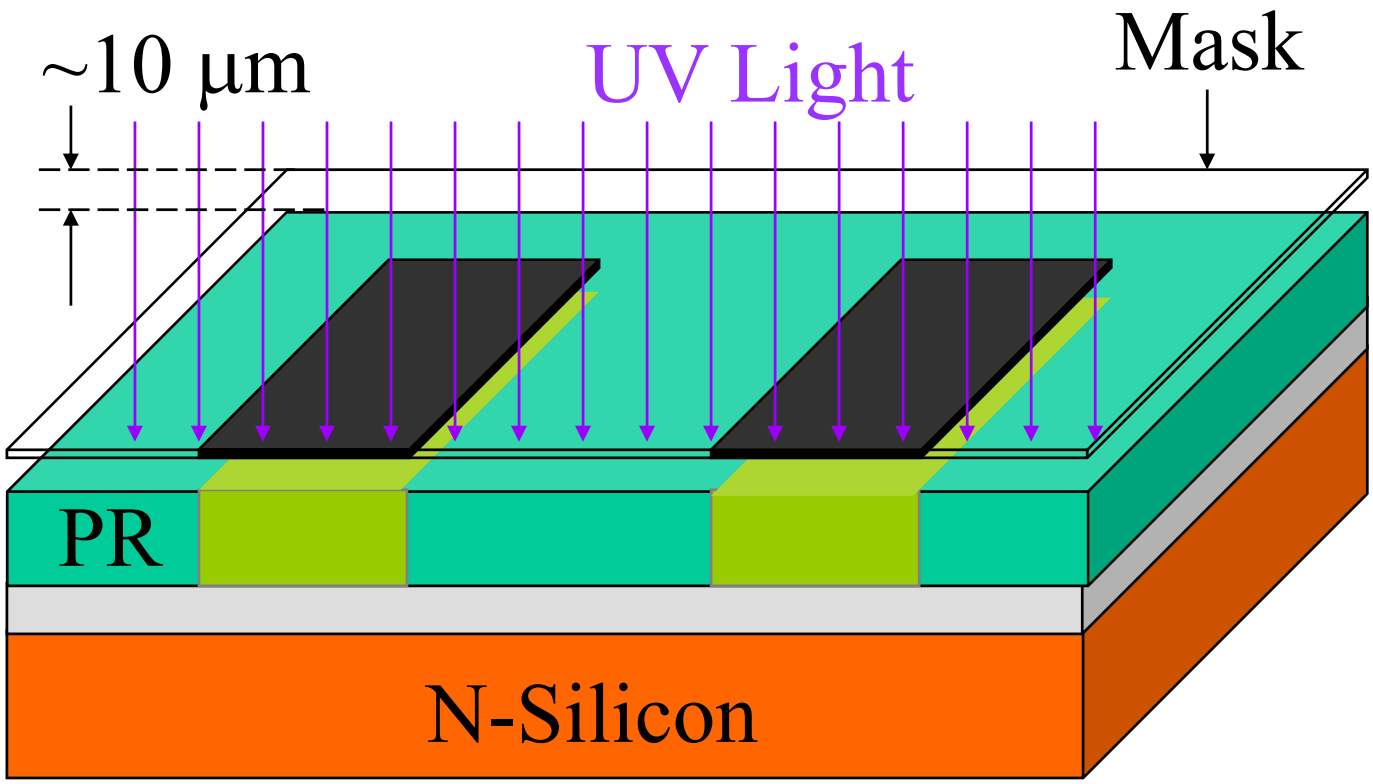
Proximity Printer

- 光罩距離光阻10 μm ~ 20 μm
- 不直接接觸
- 光罩壽命較長
- 解析度：> 3 μm

Proximity Printer



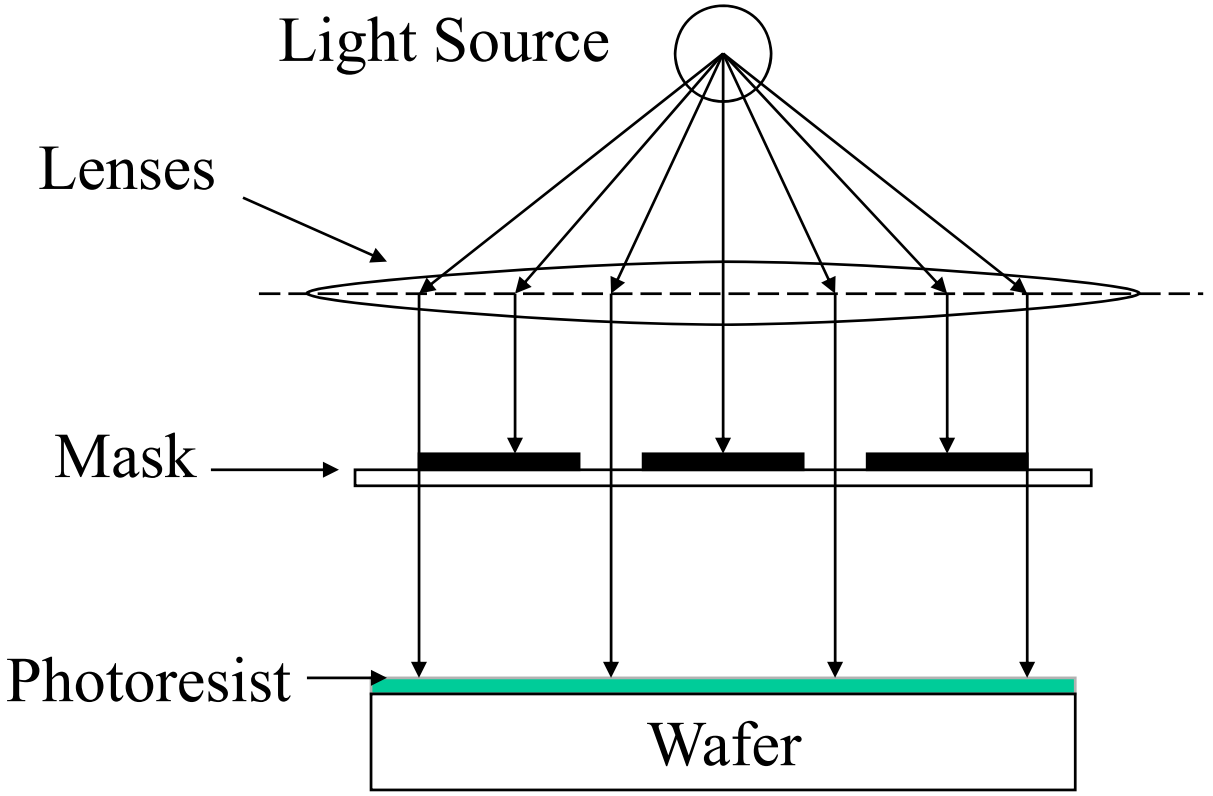
Proximity Printing



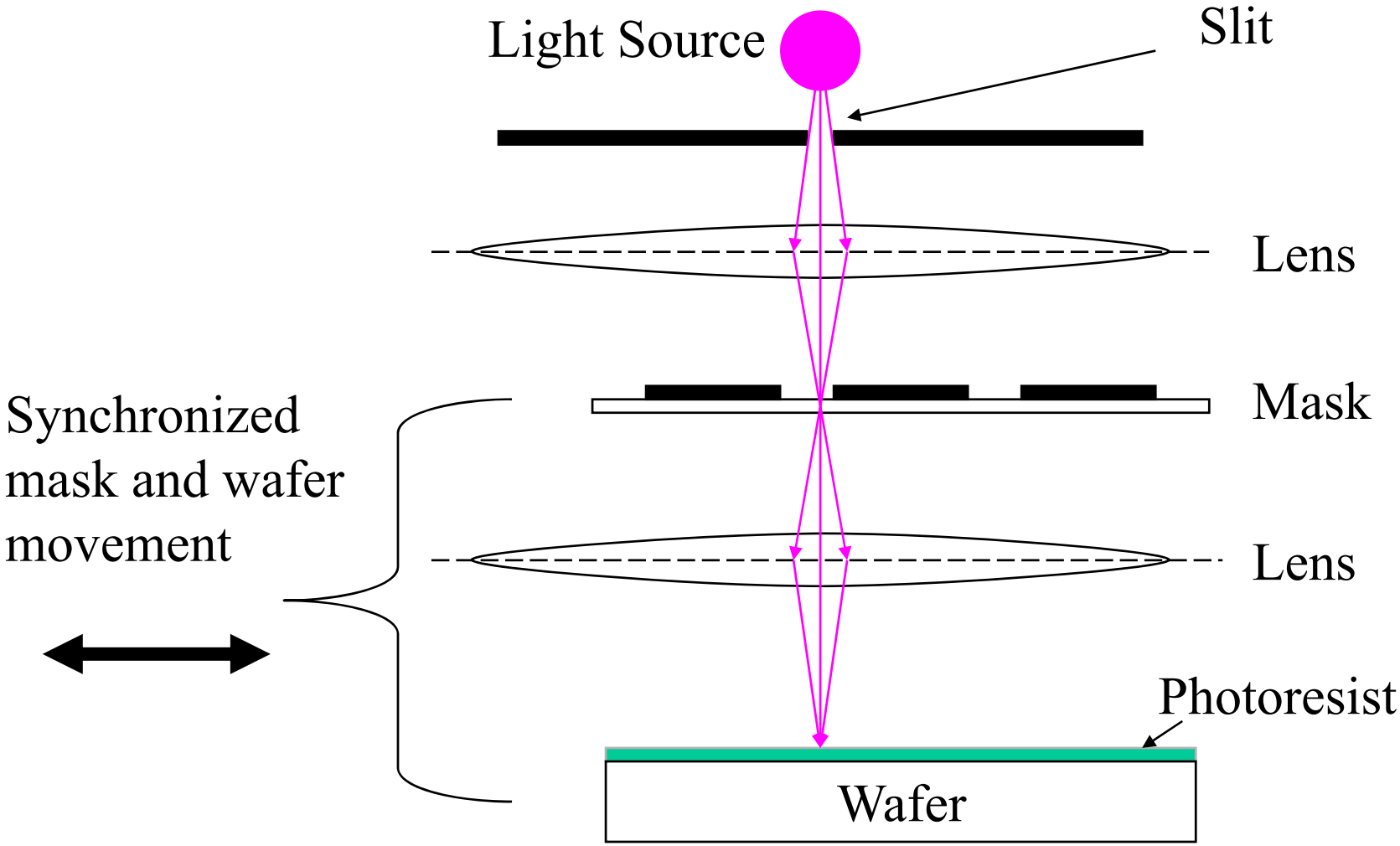
Projection Printer

- 像高射投影機一般
  - 影像以1：1比例聚焦於晶圓上
  - 最小圖形尺寸可達1 μm

Projection System



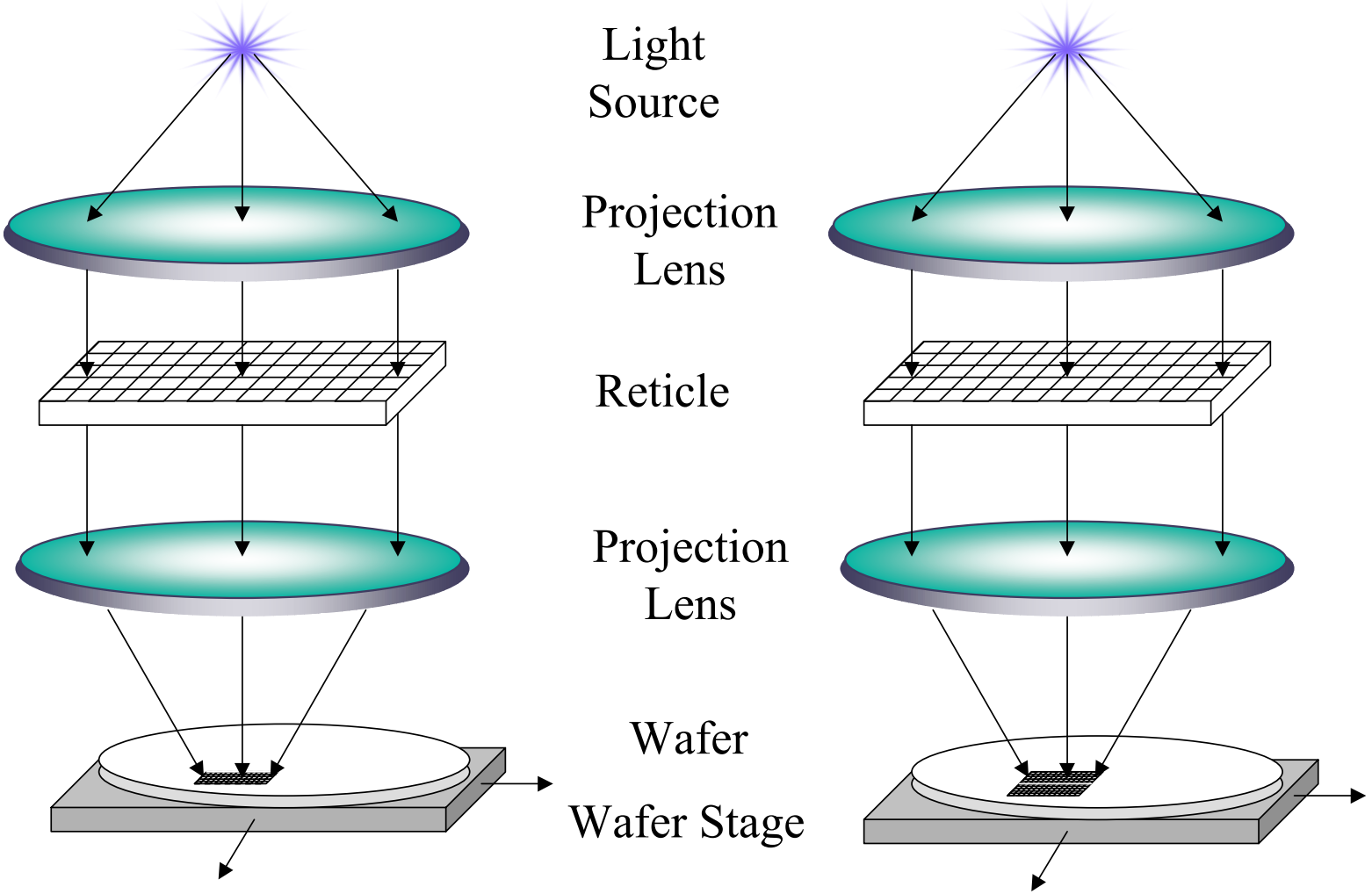
Scanning Projection System



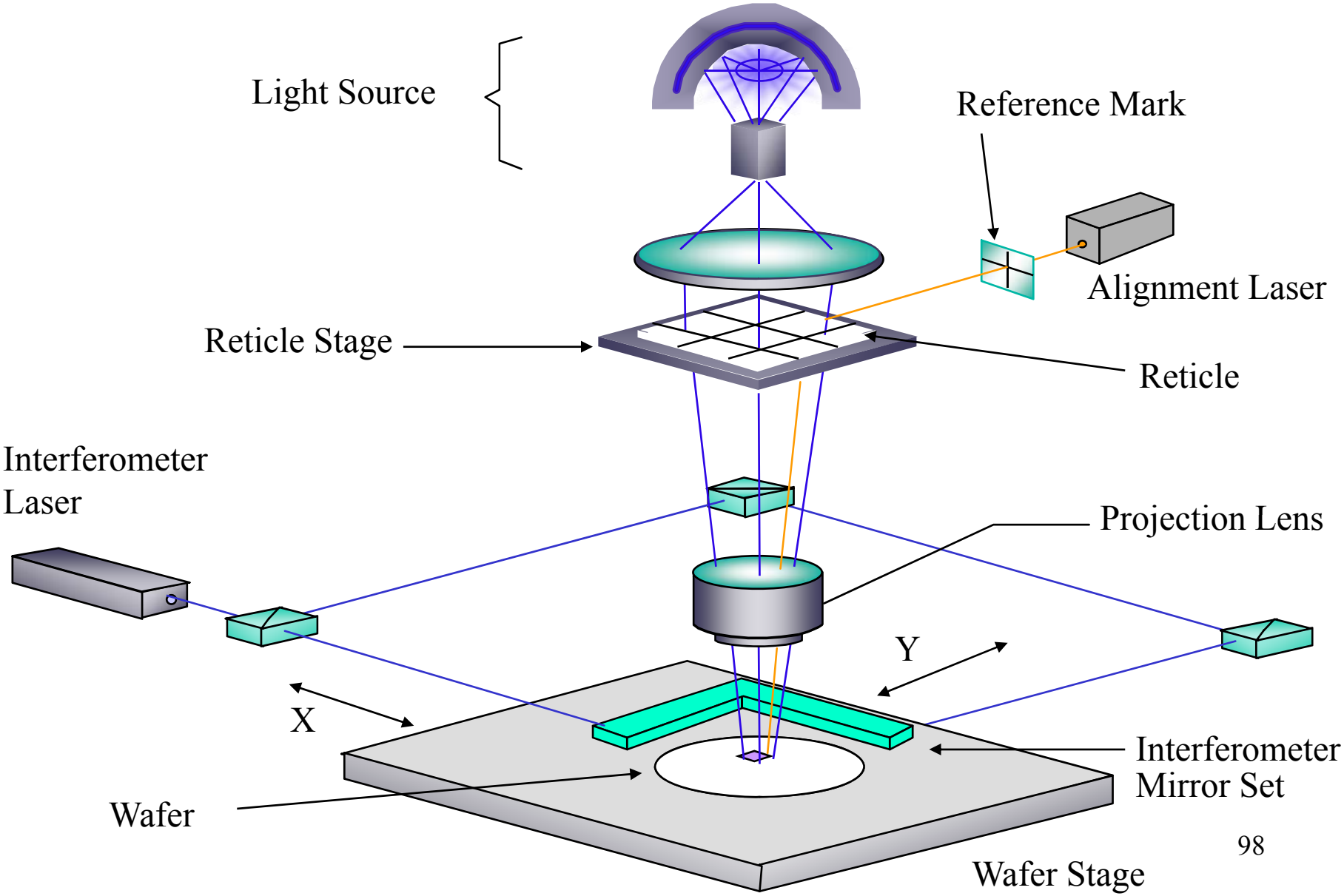
Stepper

- 在後階段的IC製程被廣泛利用的微影技術設備
- 高解析度使得縮小圖形尺寸
- 小至0.25 μm甚至更小
- 非常昂貴

Step-&-Repeat Alignment/Exposure



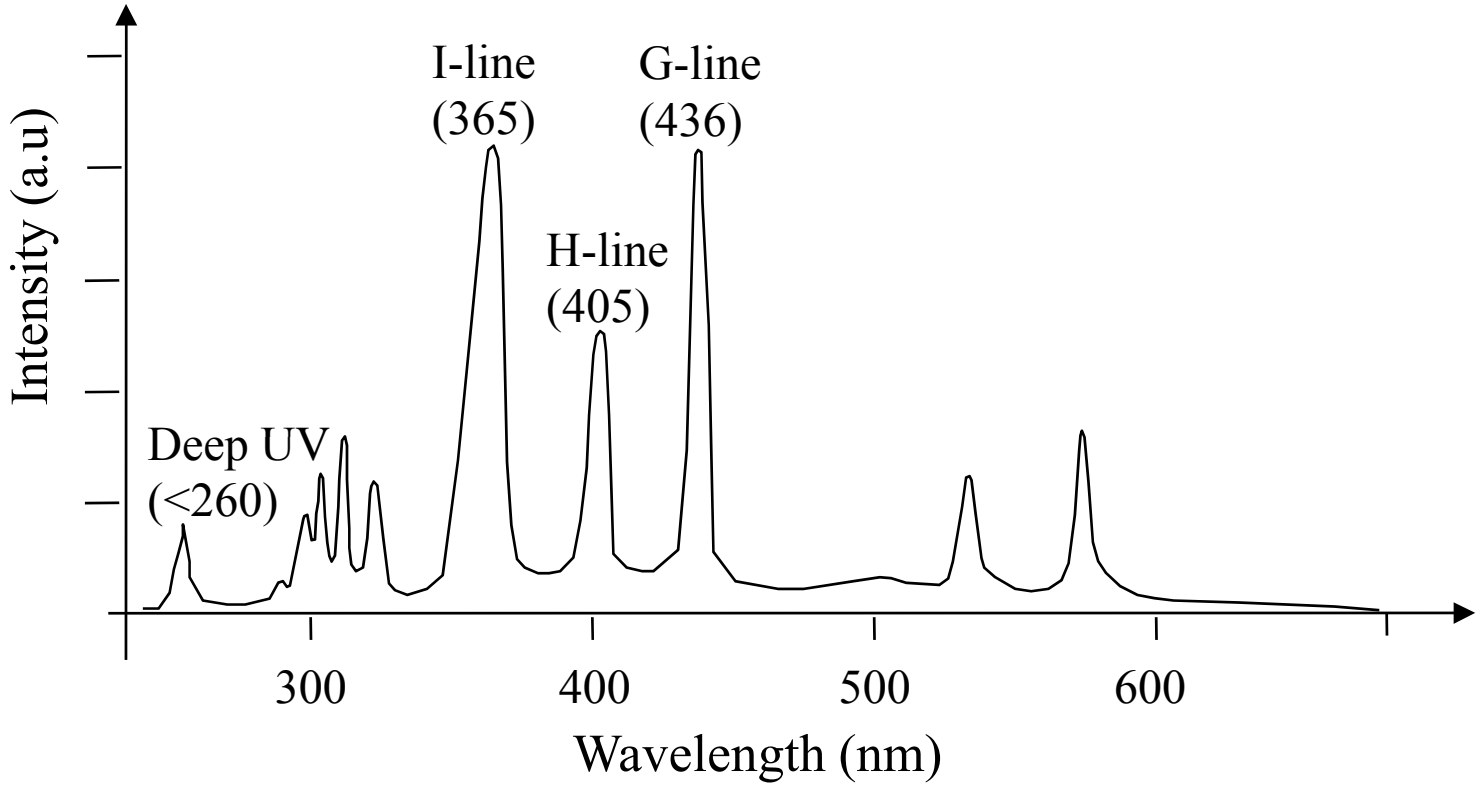
Step&Repeat Alignment System



Exposure Light Source

- 短波長
- 高強度
- 穩定的
- 高壓水銀燈
- 準分子雷射(Excimer laser)

Spectrum of the Mercury Lamp



Photolithography Light Sources

	Name	Wavelength (nm)	Application feature size (μm)
Mercury Lamp	G-line	436	0.50
	H-line	405	
	I-line	365	0.35 to 0.25
Excimer Laser	XeF	351	
	XeCl	308	
	KrF (DUV)	248	0.25 to 0.15
	ArF	193	0.18 to 0.13
Fluorine Laser	F_2	157	0.13 to 0.1

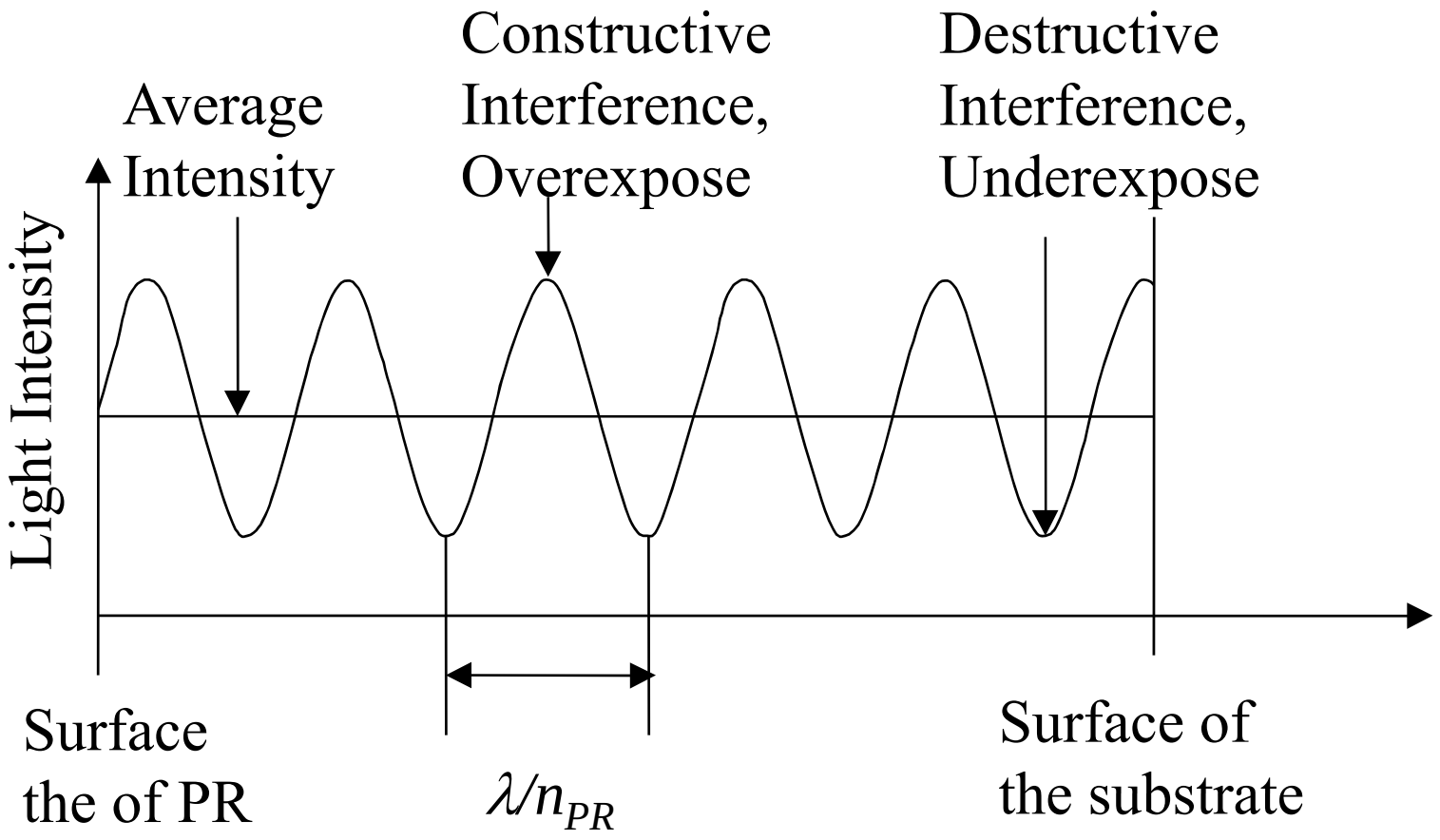
Exposure Control

- 曝光控制取決於光的強度和曝光時間
- 與照相機的曝光很類似
  - 光的強度主要由電力控制
- 光的強度可調整
- 經常校正光線的強度

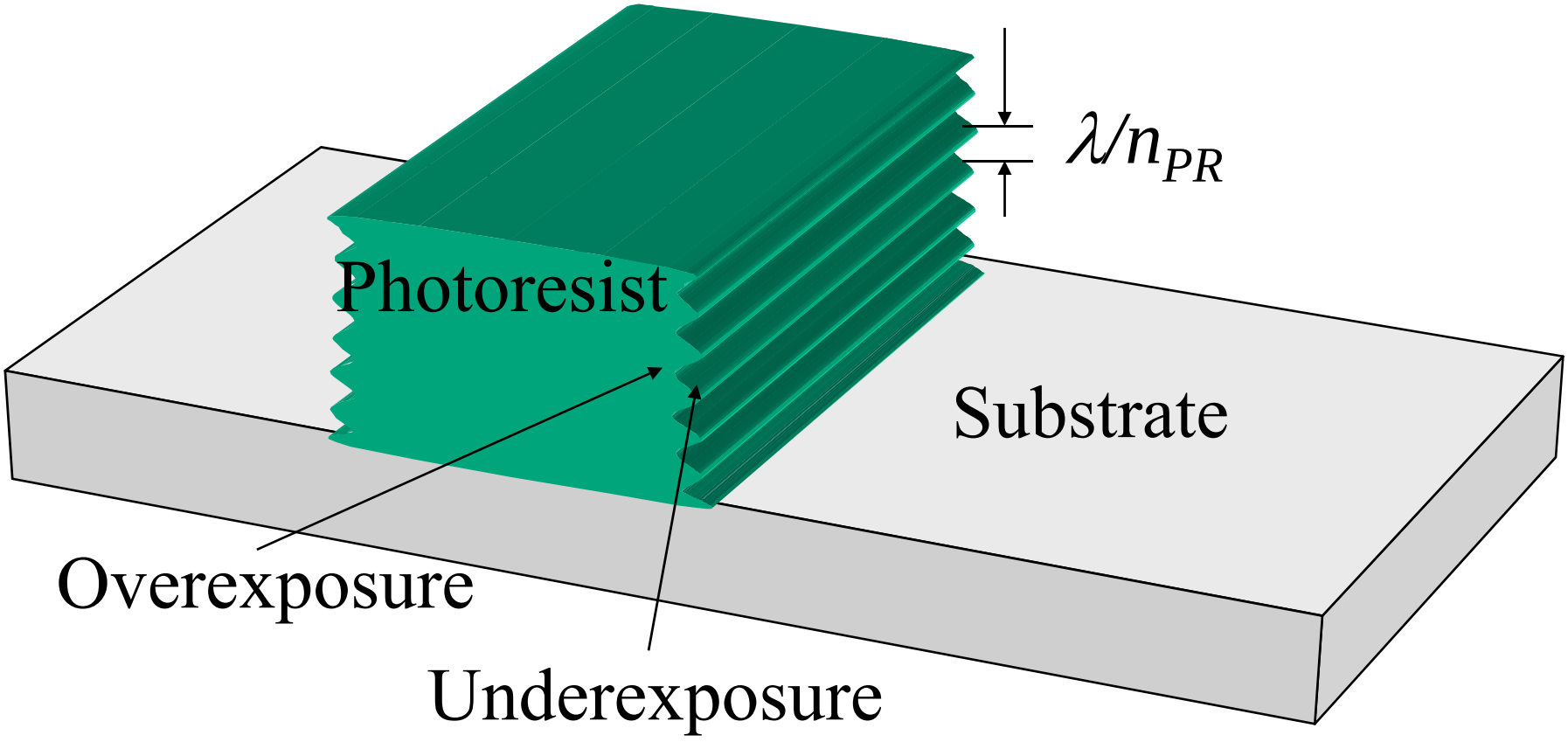
Standing Wave Effect
駐波效應

- 反射光線與入射光線產生干涉(Interference)
- 在曝光過度和曝光不足區域造成條紋狀結構
- 影響微影技術解析度

Standing Wave Intensity



Standing Wave Effect on Photoresist



Post Exposure Bake

- 光阻玻璃型過渡特性(Photoresist glass transition) 溫度T_g
- 烘烤溫度高於 T_g
- 光阻分子(molecules)產生熱運動
- 曝光過度和曝光不足的分子重新排列
- 平均駐波效應
- 平滑光阻邊緣及改善解析度

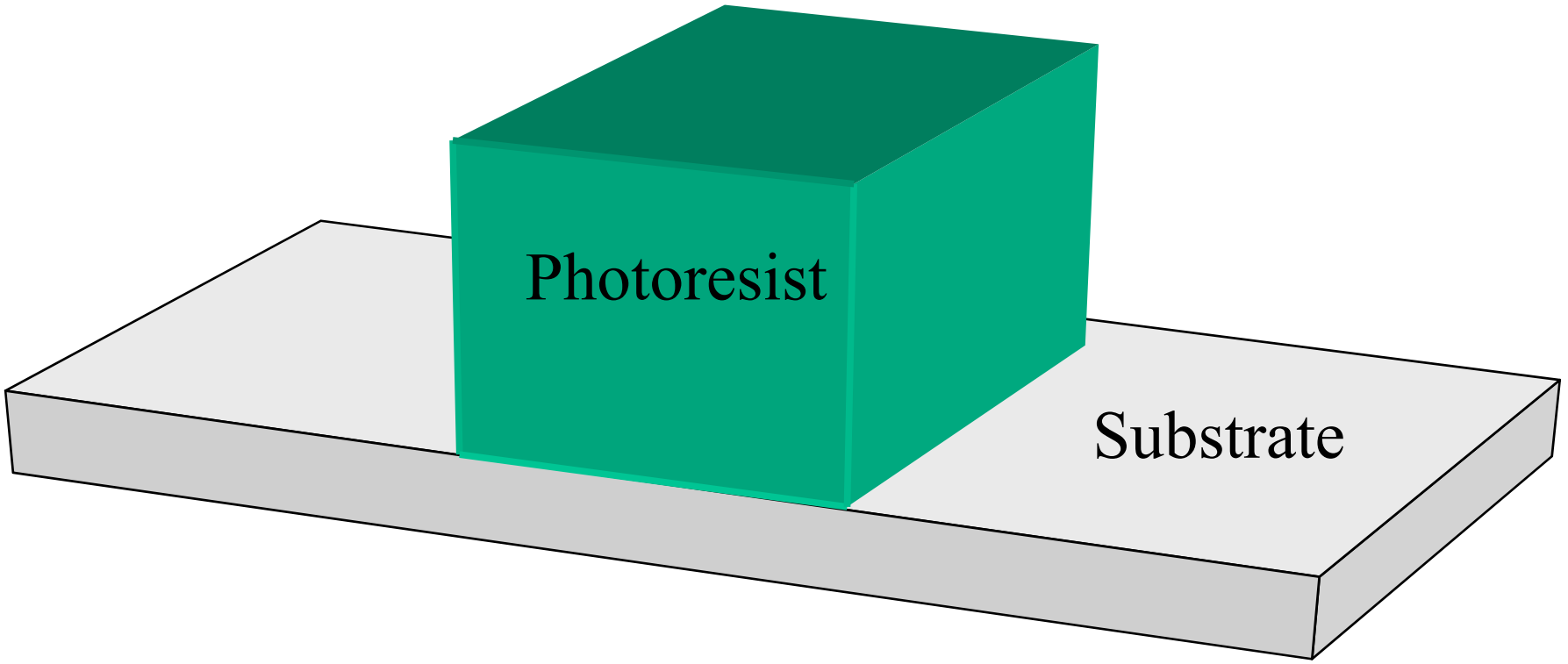
Post Exposure Bake

- 對於DUV的化學增強型光阻, PEB提供了酸擴散與增強時所需的熱量
- 在PEB製程之後,由於酸增強作用產生顯著化學變化,曝光的圖像呈現在光阻上

Post Exposure Bake

- PEB通常需要在110 to 130 °C 的平板上烘烤約 1 分鐘
- 對相同光阻而言, PEB通常需要比軟烘烤高的溫度
- 不足的PEB將無法完全消除駐波的圖案
- 過度烘烤造成聚合作用且影響光阻顯影

PEB Minimizes Standing Wave Effect



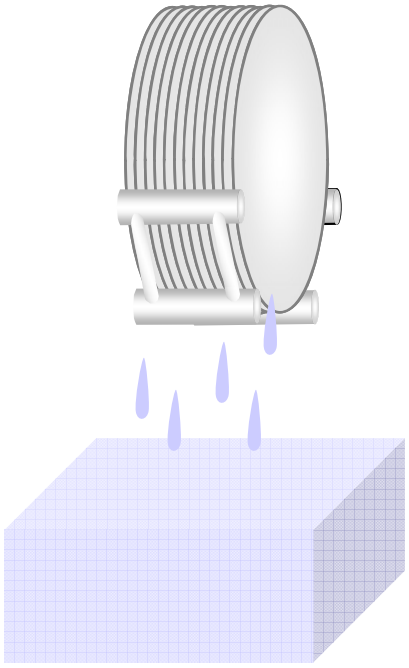
Wafer Cooling

- 在PEB後且在顯影製程前晶圓被置於冷卻平板上冷卻至室溫
- 高溫會增加化學反應使之過度顯影
- 損失PR CD

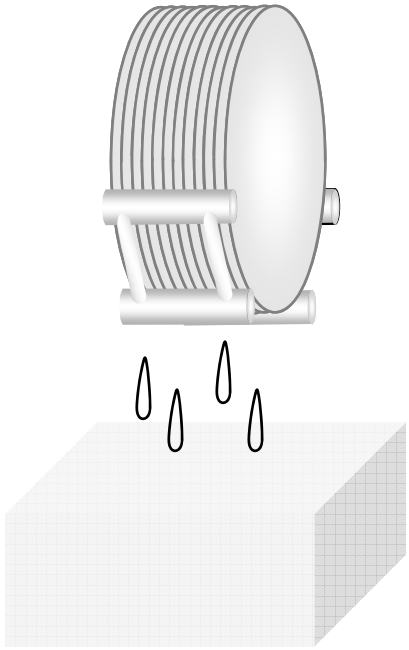
Development

- 顯影劑溶解光阻曝光的部分
- 從光罩或倍縮光罩(reticle)轉印圖案至光阻上
- 三個基本步驟：
  - 顯影(Development)
  - 洗滌(Rinse)
  - 乾燥(Dry)

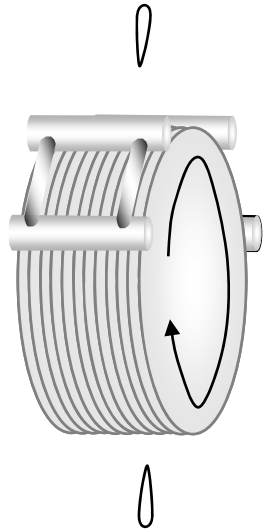
Development: Immersion



Develop



Rinse

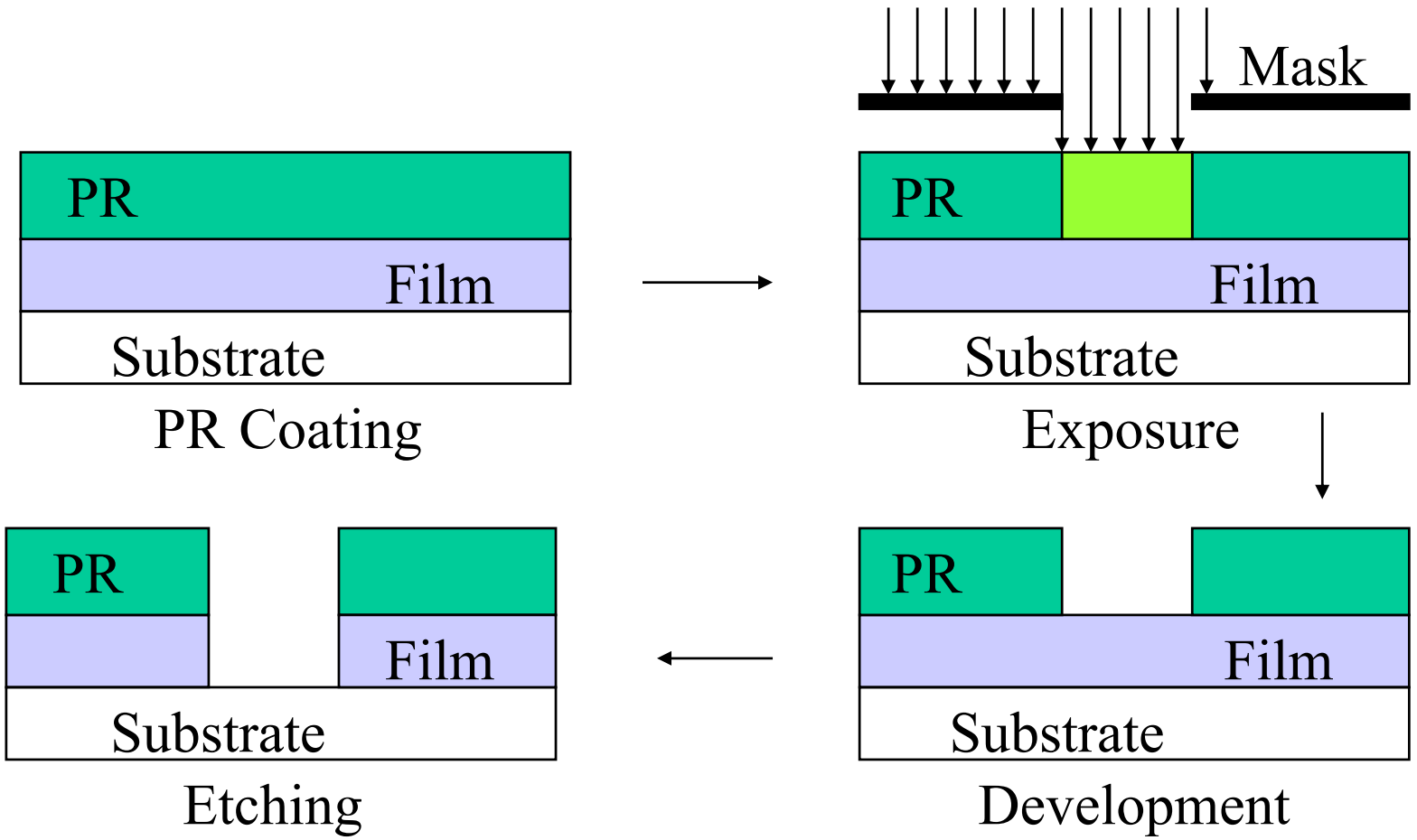


Spin Dry

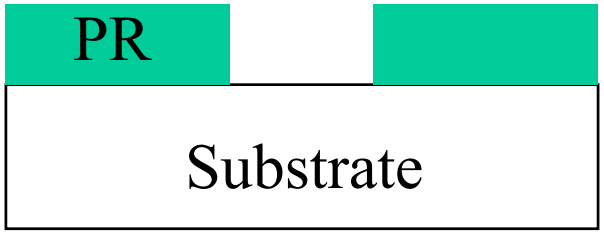
Developer Solution

- 正光阻通常使用弱鹼溶劑
  - 最常使用的一種是氫氧化四甲基氨(tetramethyl ammonium hydride),或TMAH ($(CH_3)_4NOH$).

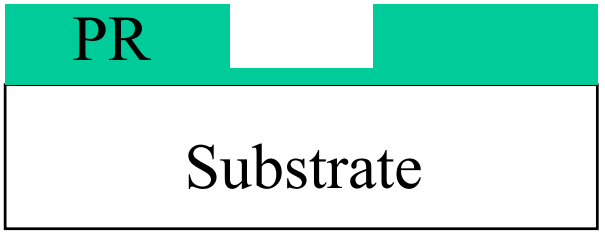
Development



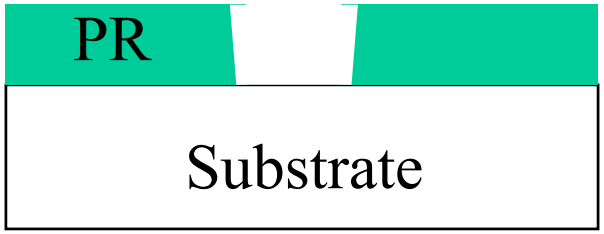
Development Profiles



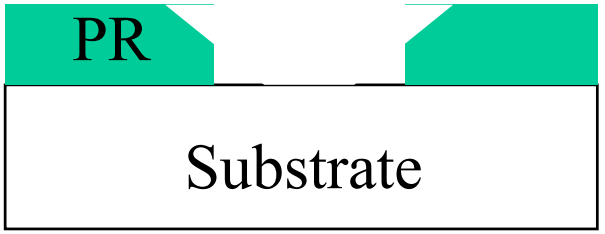
Normal Development



Incomplete Development



Under Development

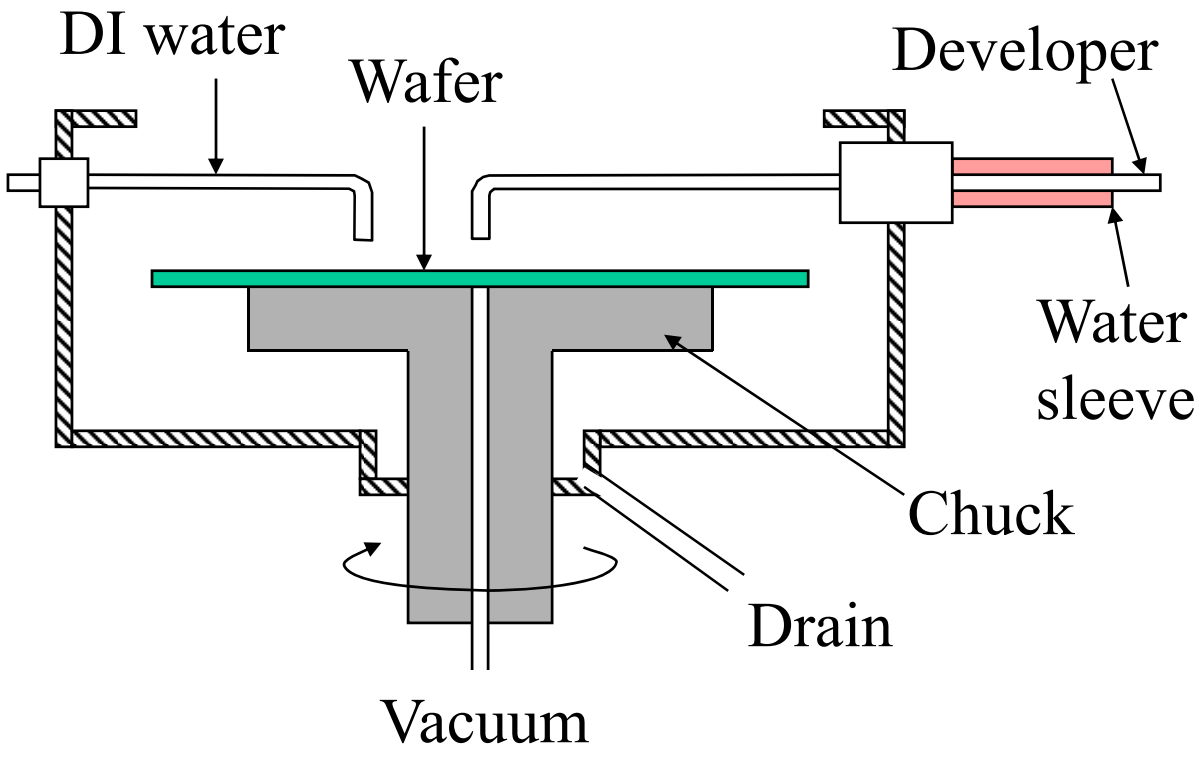


Over Development

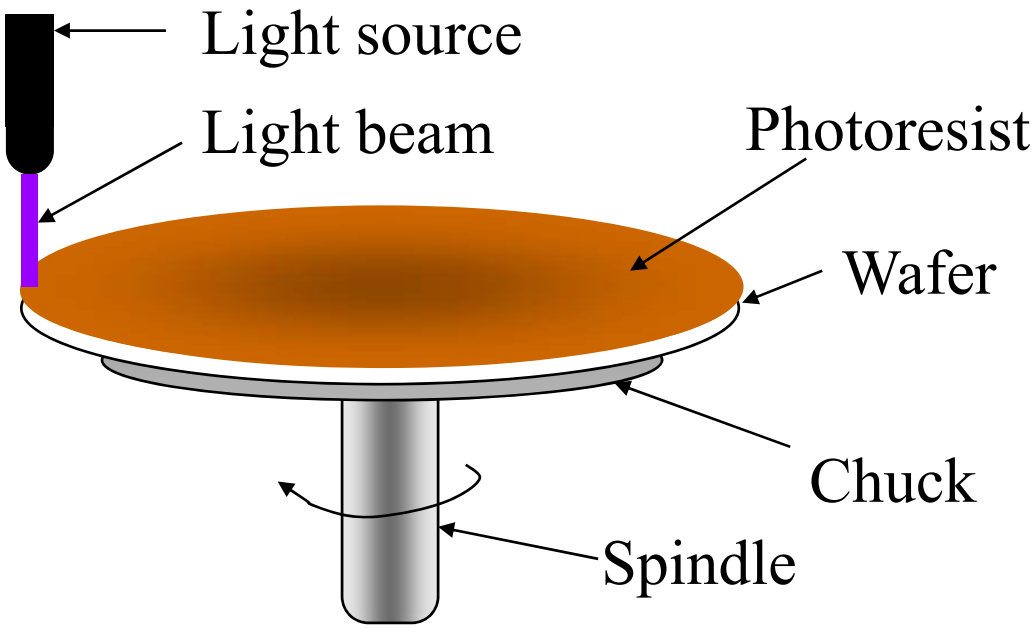
Developer Solutions

	Positive PR	Negative PR
Developer	TMAH	Xylene
Rinse	DI Water	n-Butylacetate

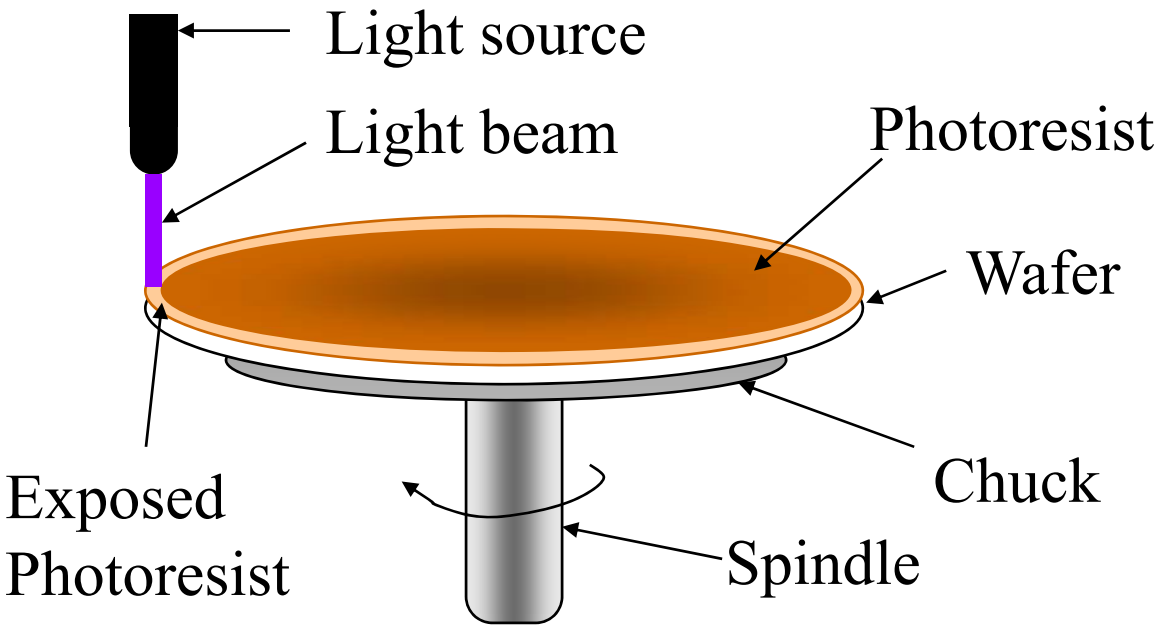
Schematic of a Spin Developer



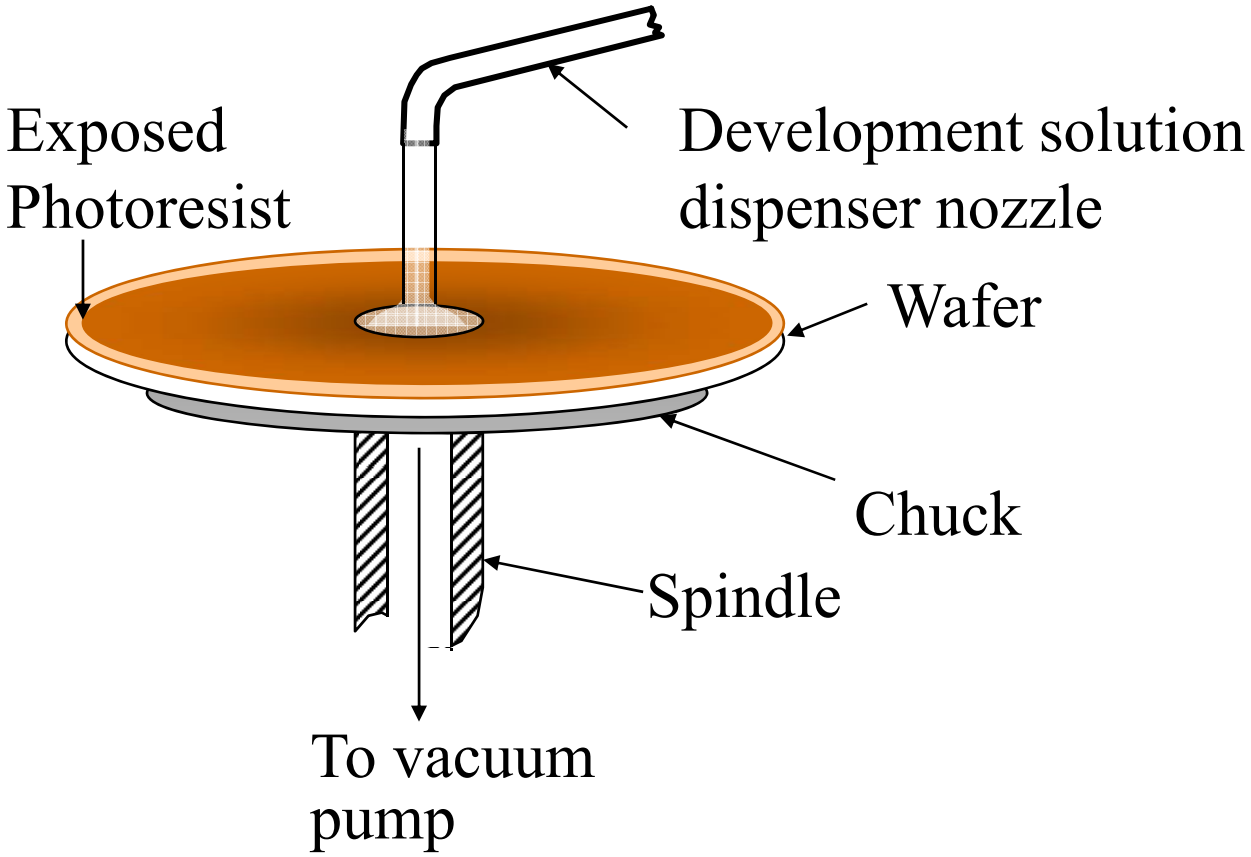
Optical Edge Bead Removal Exposure



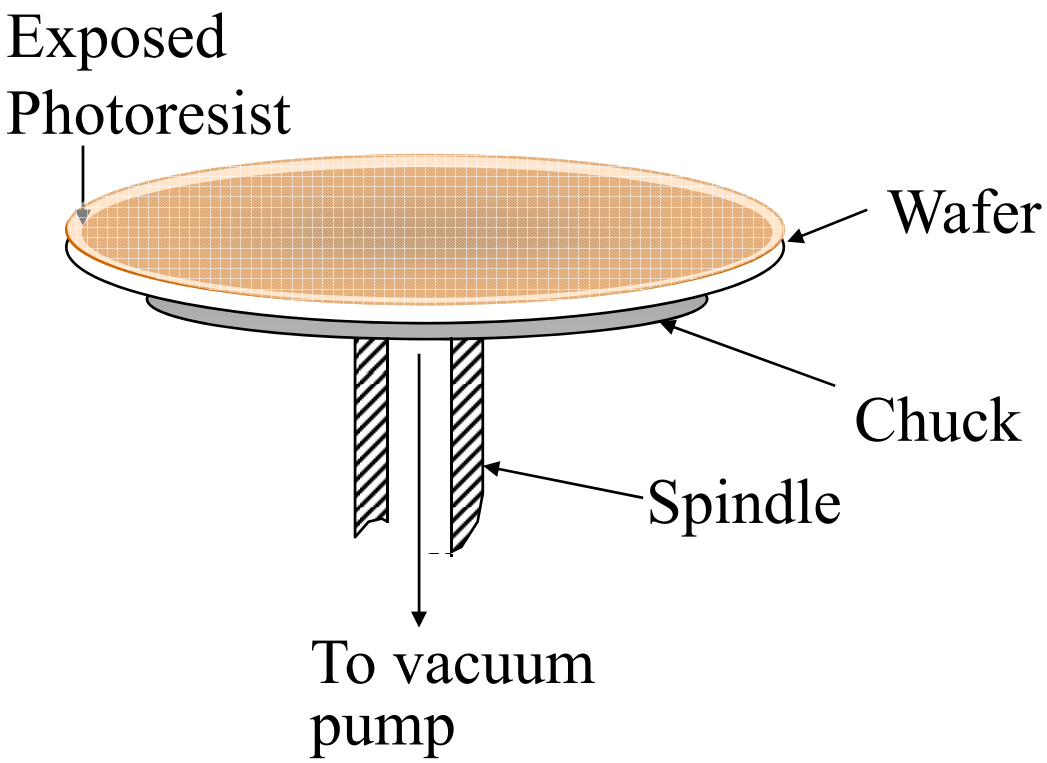
Optical Edge Bead Removal Exposure



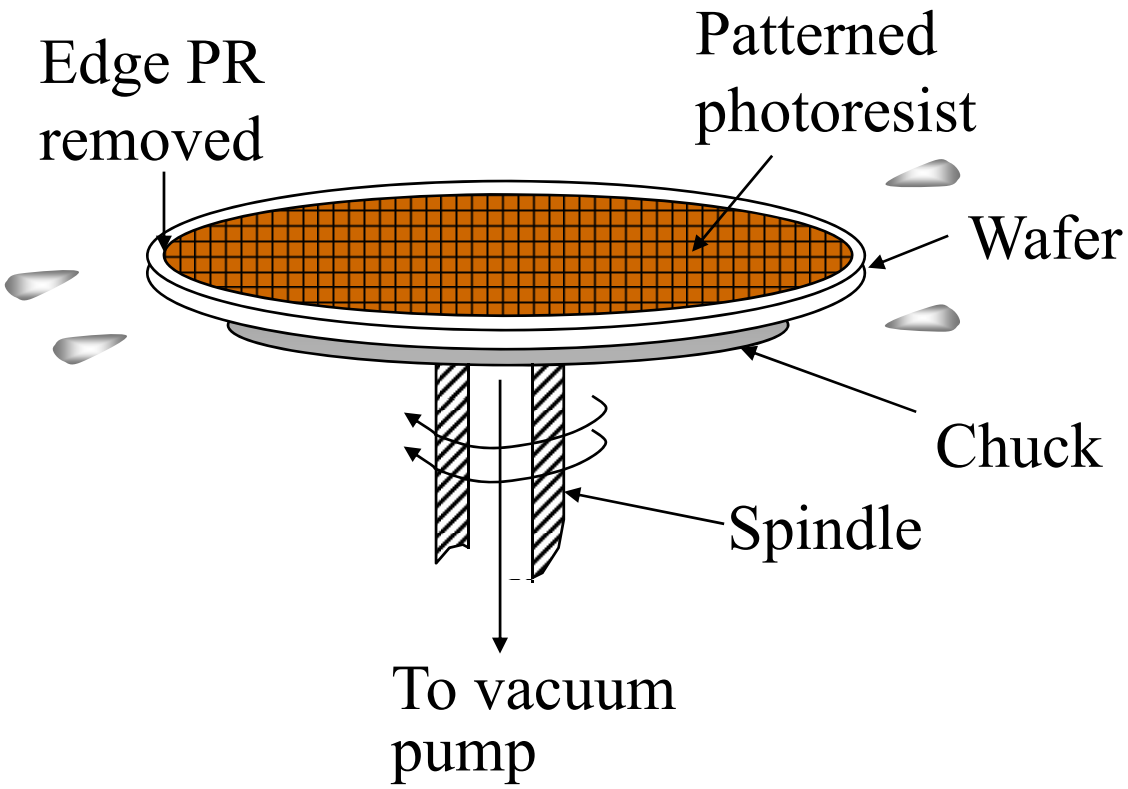
Applying Development Solution



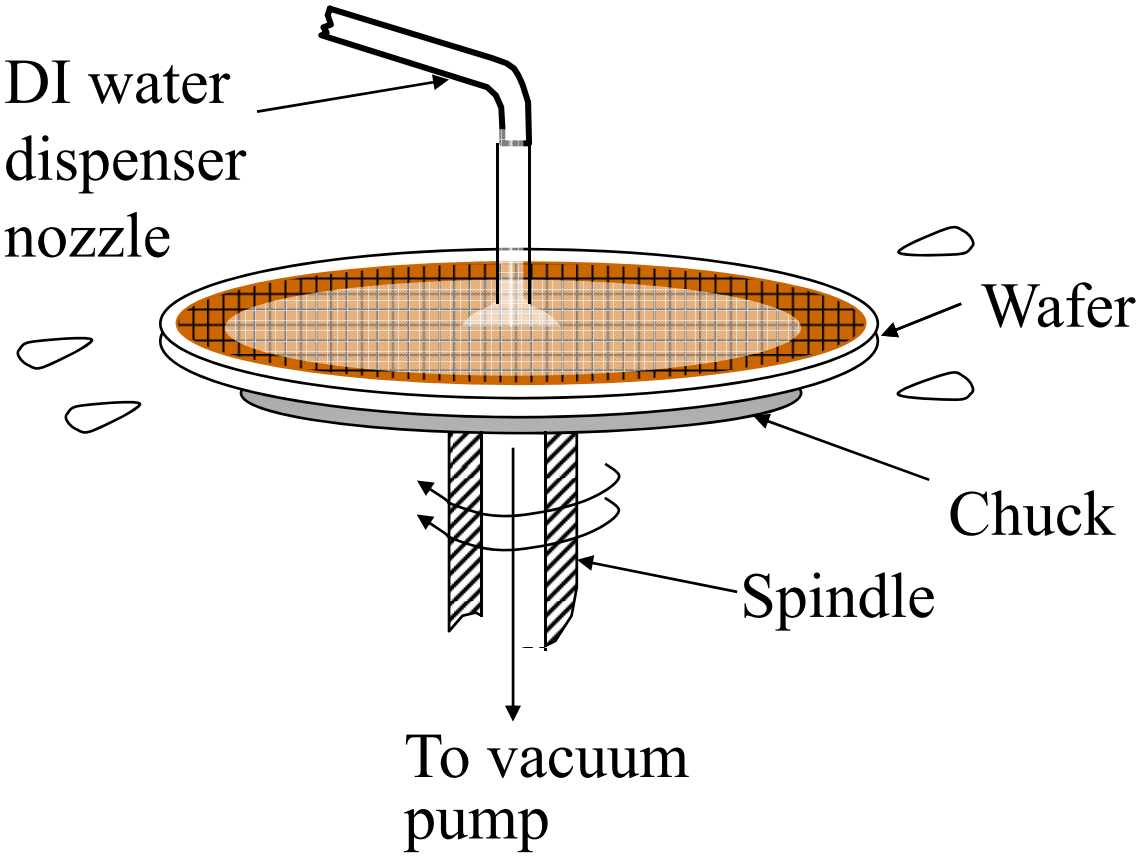
Applying Development Solution



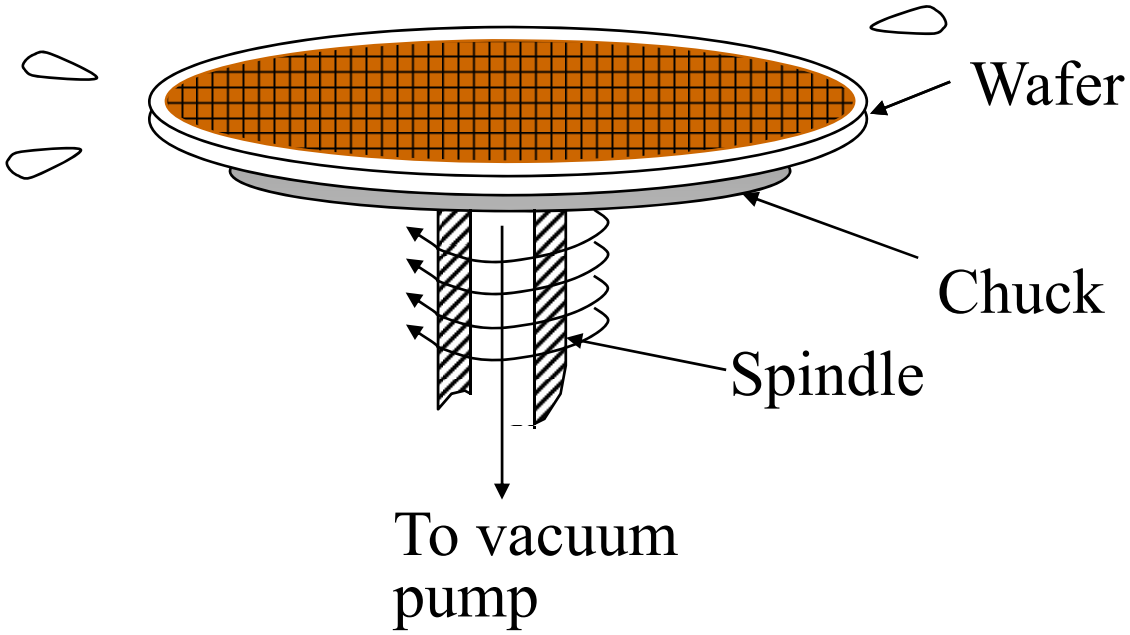
Development Solution Spin Off



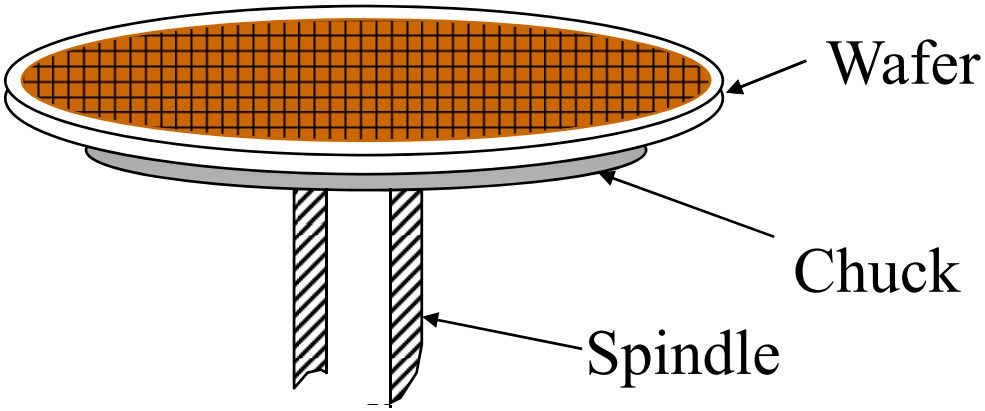
DI Water Rinse



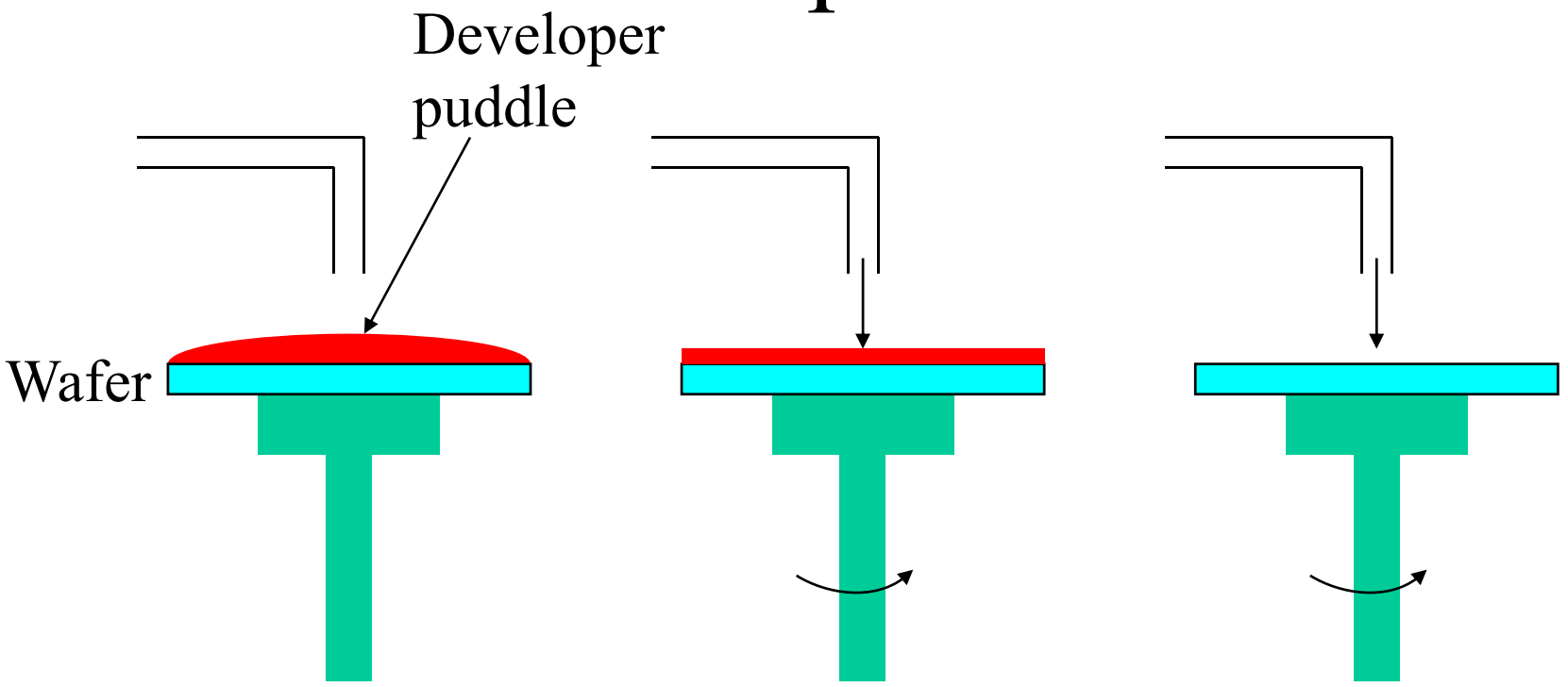
Spin Dry



Ready For Next Step



Development



Form puddle

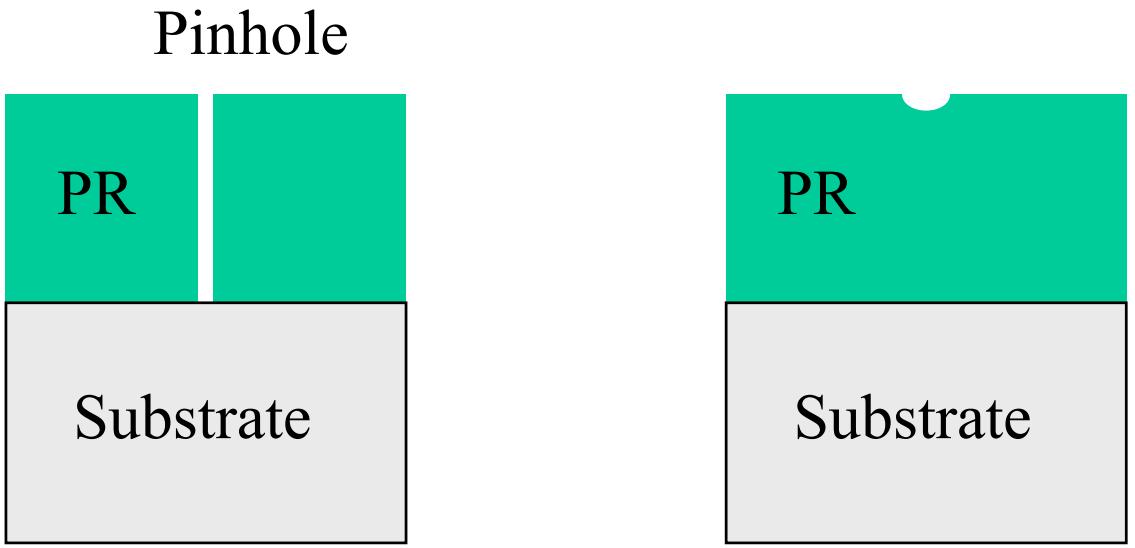
Spin spray

Spin rinse
and dry

Hard Bake

- 蒸發光阻內所有的溶劑
- 改進光阻蝕刻與離子佈植的抵抗力
- 增進光阻在晶圓上的附著力
- 使光阻聚合與穩定
- 光阻流動並填滿針孔

PR Pinhole Fill by Thermal Flow



Hard Bake

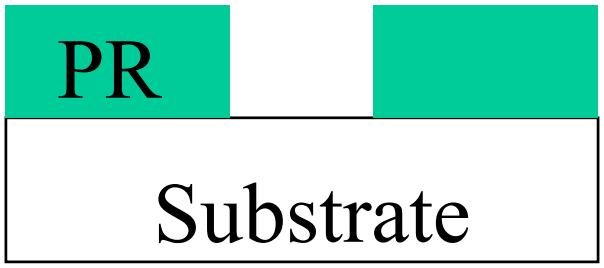
- 通常使用熱平板
- 在檢視之後可以在烤箱中完成
  - 硬烘烤溫度：100 to 130 °C
  - 烘烤時間大約 1 至 2 分鐘
  - 對相同光阻而言, 硬烘烤通常需要比軟烘烤高的溫度

Hard Bake

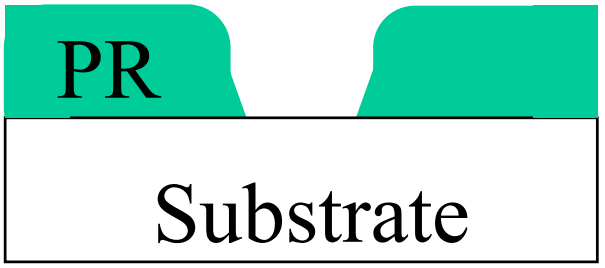
- 烘烤不足
  - 光阻聚合作用不足
    - 光阻高蝕刻速率
    - 附著力變差
- 烘烤過度
  - 光阻流動過多且造成解析度變差

Photoresist Flow

- Over baking can causes too much PR flow, which affects photolithography resolution.



Normal Baking

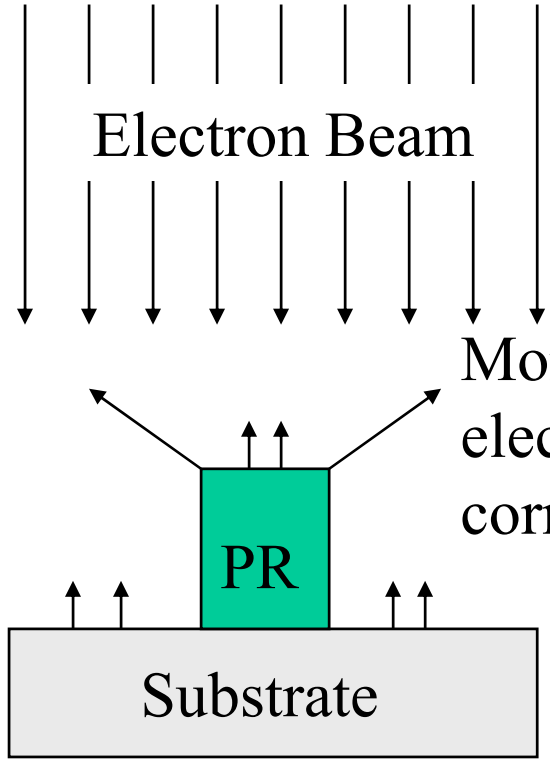


Over Baking

Pattern Inspection

- 沒通過檢視光阻被剝除且送回重做
  - 光阻圖案是暫時的
  - 蝕刻或離子佈植後圖案是永久的
- 微影技術製程可以重做
- 蝕刻或離子佈植後不能重做
- 掃描式電子顯微鏡(Scanning electron microscope,SEM)
- 光學顯微鏡(Optical microscope)

Electron Microscope

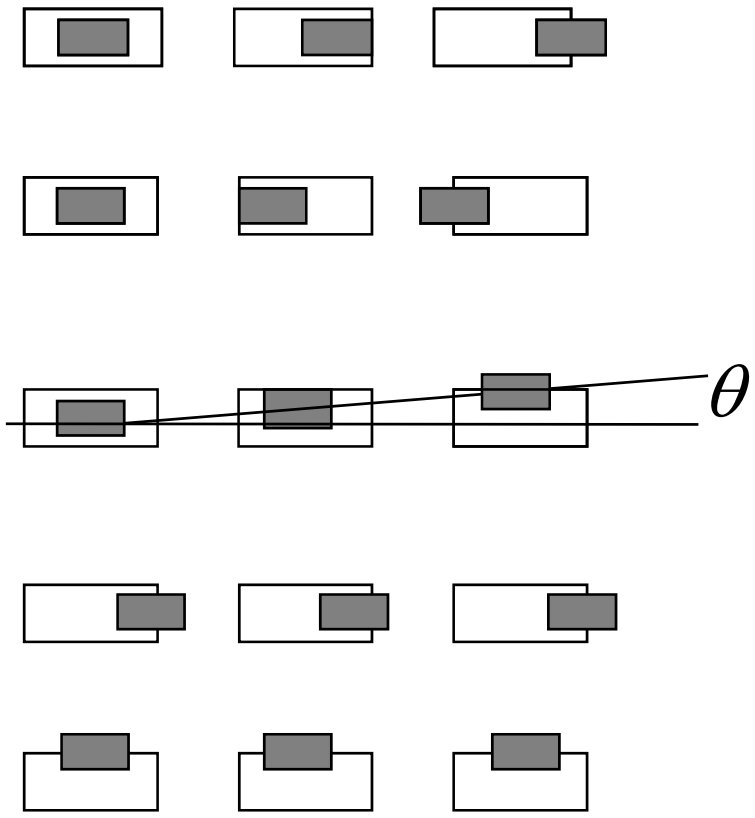


Less secondary electrons on the sidewall and plate surface

Pattern Inspection

- 覆蓋或對準
  - 插出(run-out) ,插入(run-in),倍縮光罩旋轉, 晶圓旋轉, x方向的錯置(misplacement),y方向的錯置(misplacement)
- 關鍵尺寸(CD)
- 表面上不合規格的事物,如刮痕、針孔、瑕疵、污染物

Misalignment Cases



Run-out

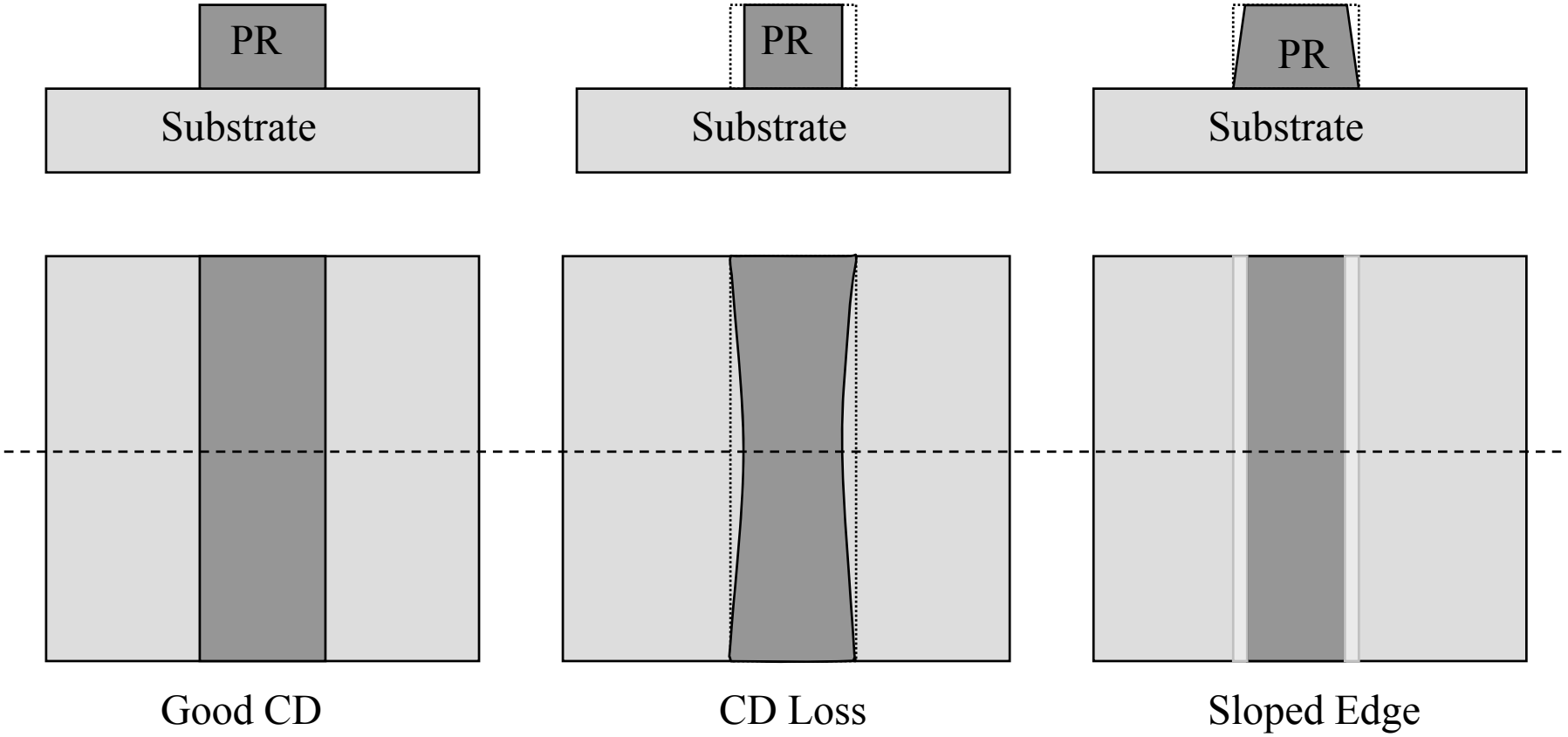
Run-in

Reticle rotation
Wafer rotation

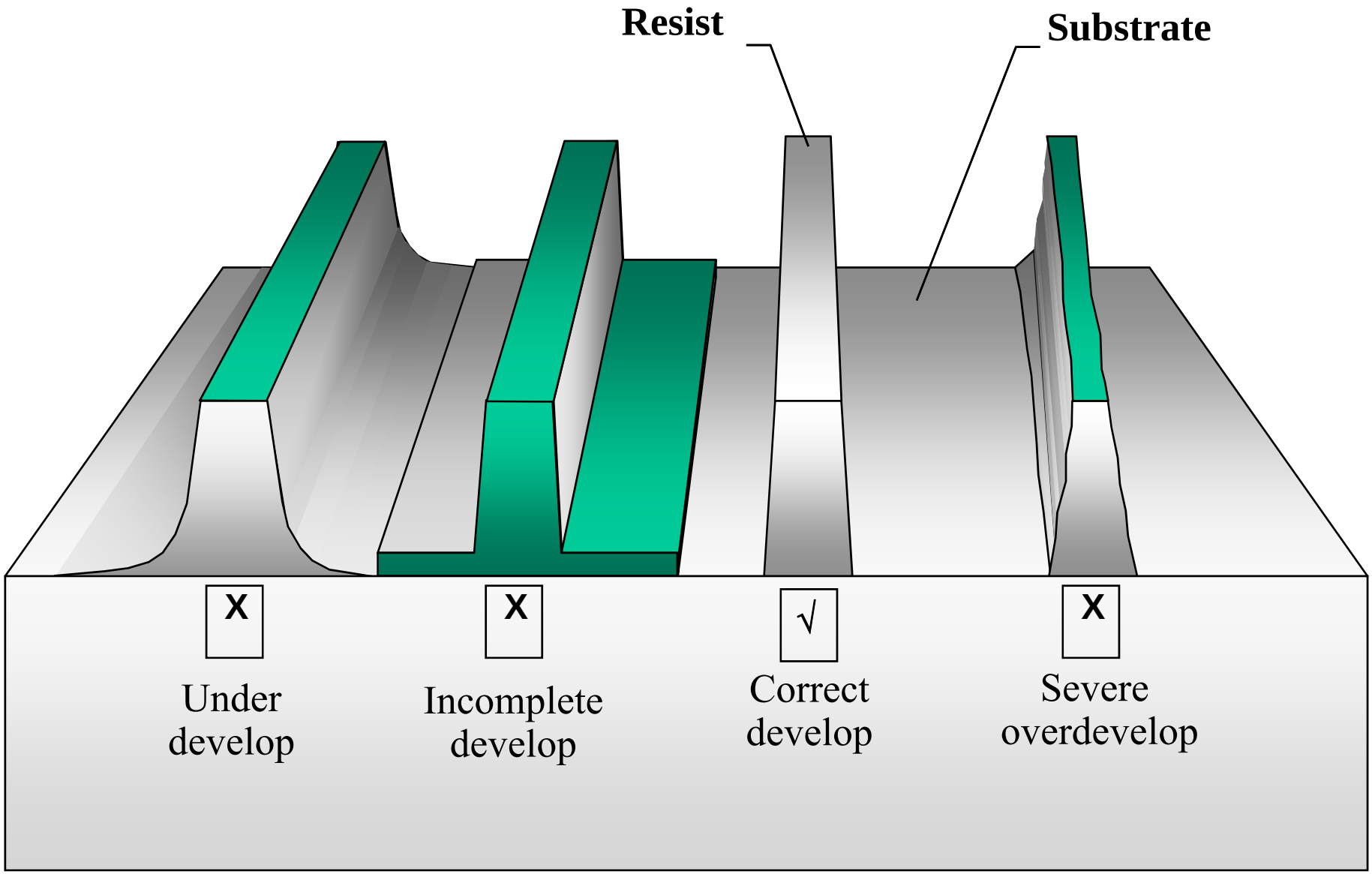
Misplacement in x-direction

Misplacement in y-direction

Critical Dimension



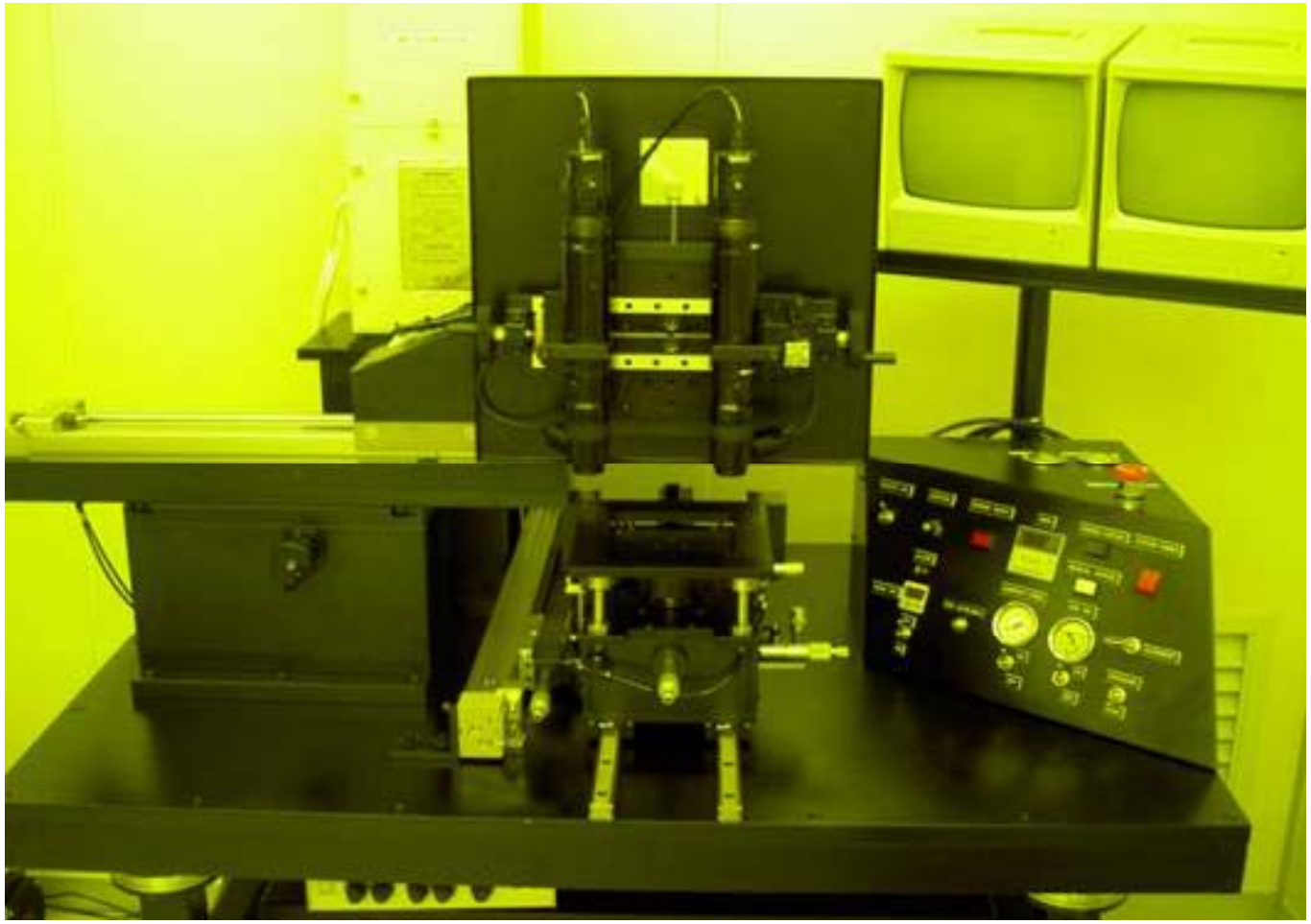
Photoresist Development Problems



Pattern Inspection

- 假如晶圓通過檢視, 會從光學區間移出並進入下一個製程

- 蝕刻或是離子佈植步驟



- 光罩對準機**(Mask Aligner and Exposure System)** 365 nm 400 nm Resolution 0.6μm

Future Trends

- 縮小尺寸
- 更高解析度
- 減短波長
  - 相位移光罩(Phase-shift mask)

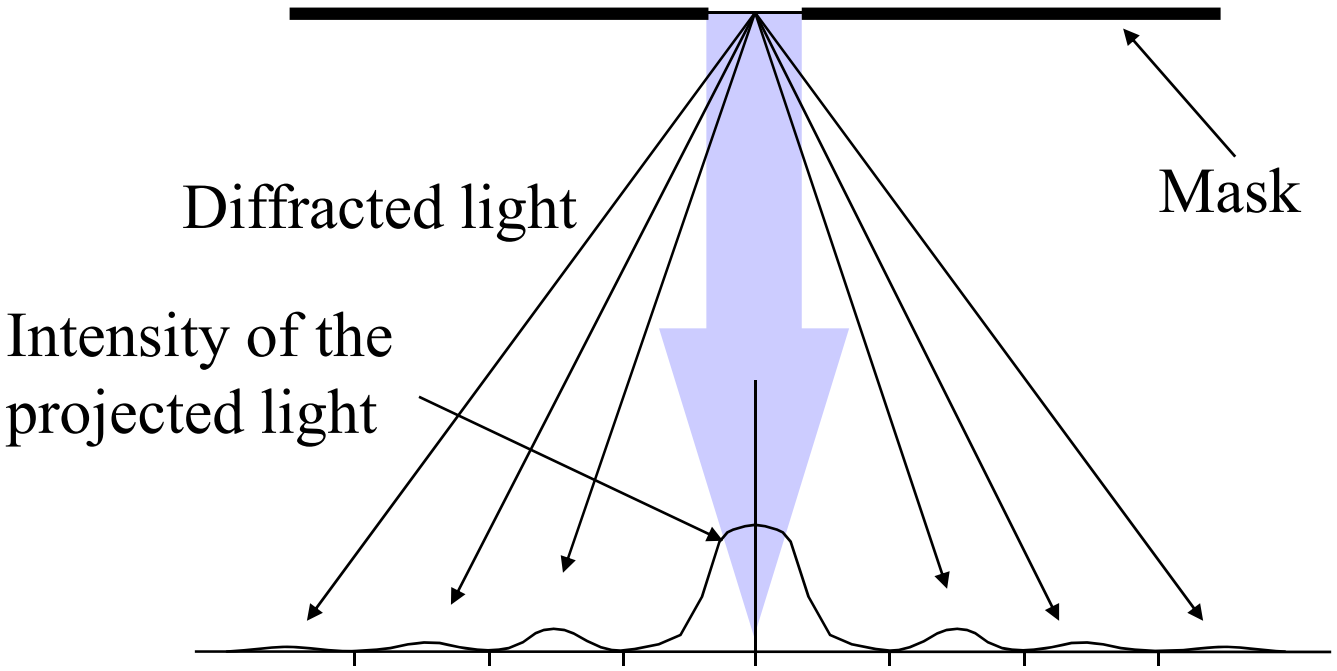
Optical Lithography

- 光學
  - 光線繞射(diffraction)
- 解析度
  - 景深(Depth of focus,DOF)

Diffraction

- 基本光學特性
- 光是電磁波
- 波繞射
- 繞射影響解析度

Light Diffraction Without Lens

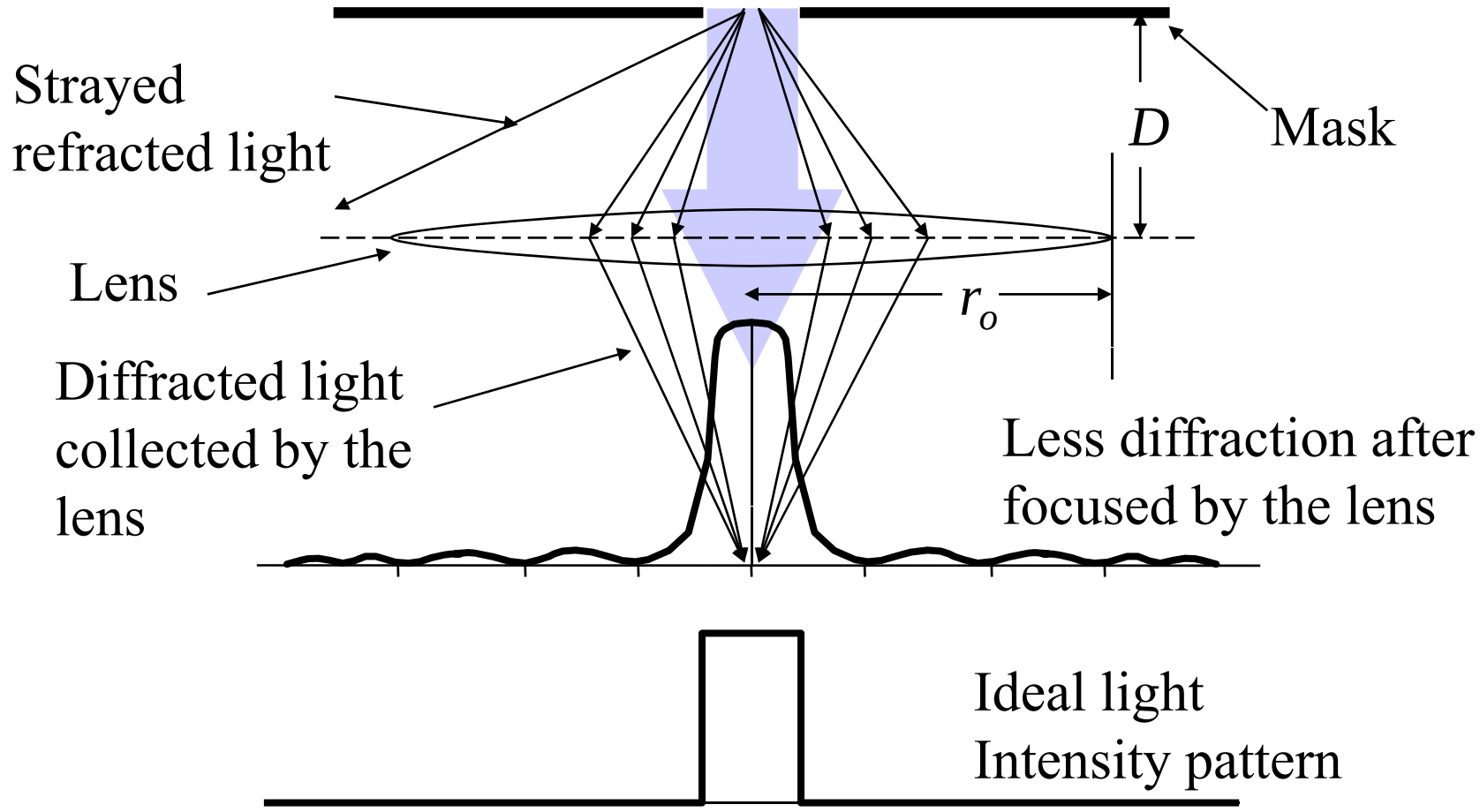


Diffraction Reduction

- 短波長的波產生較少繞射
- 光學透鏡將繞射光聚焦改善解析度

$$Diffraction \propto \frac{\lambda}{d}$$ d為孔徑大小

Light Diffraction With Lens



Numerical Aperture

- 數值孔徑*(NA)*是指透鏡收集繞射光的能力
- $NA = 2\, r_0 / D$
  - r_0 : 透鏡半徑
  - D : 物體到透鏡的距離
- 高數值孔徑的透鏡可以收集更多的繞射光線及產生明顯的圖案

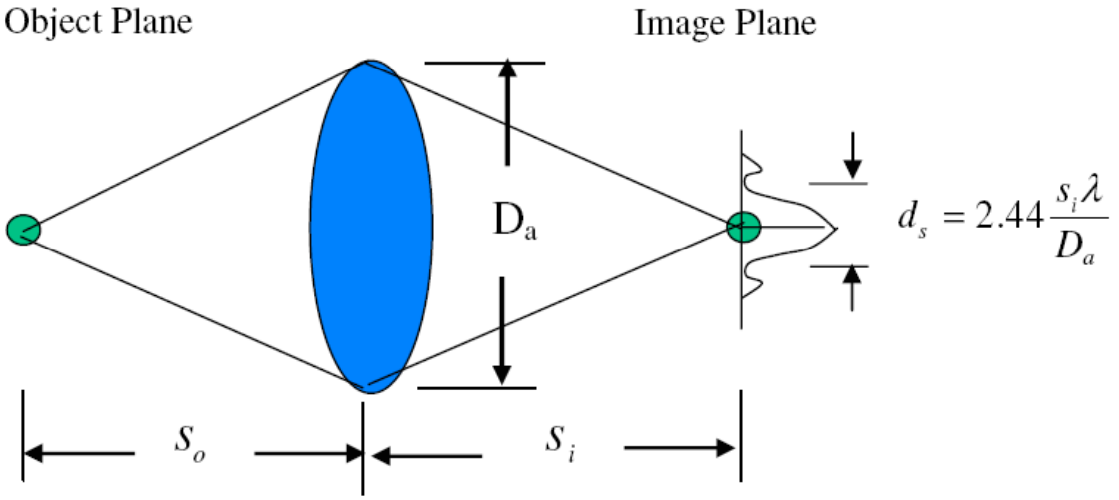
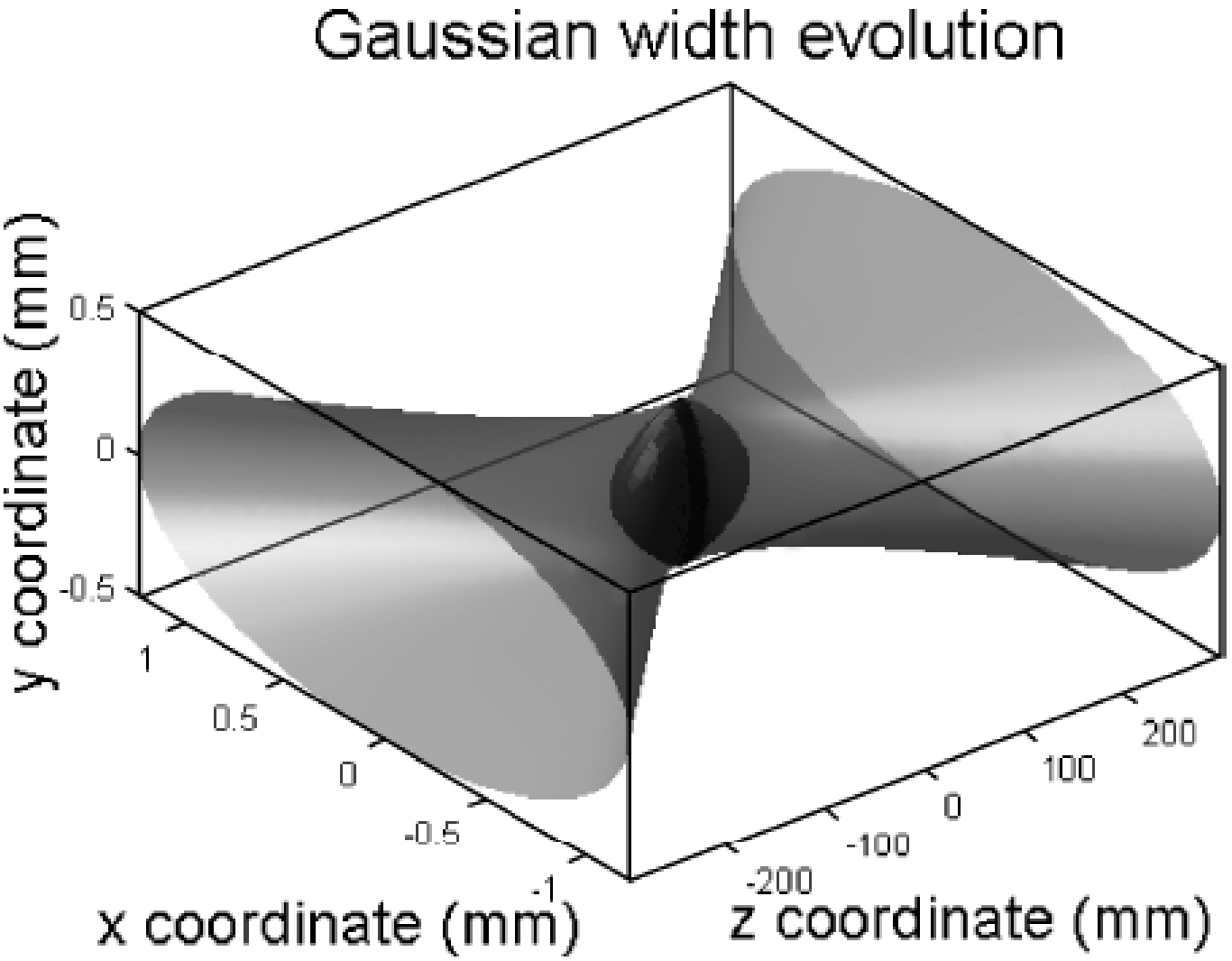


Figure 1. Schematic of a single thin lens with aperture diameter, D_a. The point spread function through a circular aperture is the well-known Airy function of width, $d_s = 2.44 s_i \lambda / D_a$.

Resolution

$$R = \frac{K_1 \lambda}{NA}$$


Gaussian width evolution
y coordinate (mm)
0.5
0
-0.5
1
0.5
0
-0.5
-1
x coordinate (mm)
200
100
0
-100
-200
z coordinate (mm)

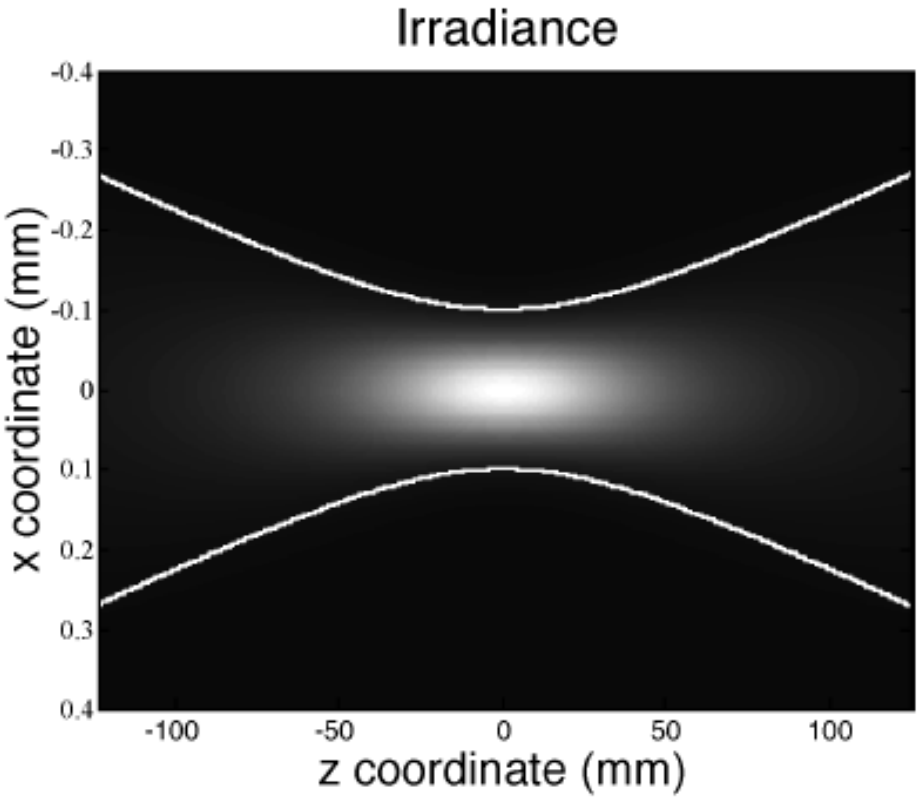
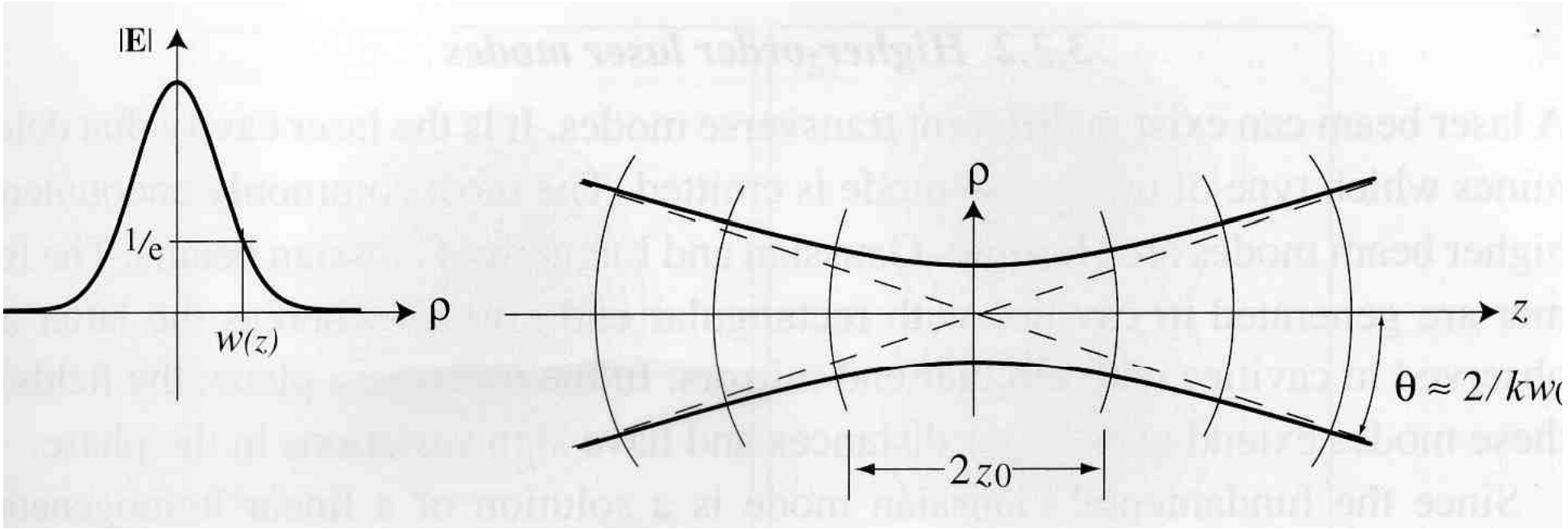


Fig. 1 Map of the irradiance distribution of a Gaussian beam. The bright spot corresponds with the beam waist. The hyperbolic white lines represent the evolution of the Gaussian width when the beam propagates through the beam waist position. The transversal Gaussian distribution of irradiance is preserved as the beam propagates along the z axis.


|E|
1/e
w(z)
ρ
ρ
z
θ ≈ 2/kw(
2z0

Resolution

- 決定於光線的波長及系統的數值孔徑
- 解析度可以表示為

$$R = \frac{K_1 \lambda}{NA}$$

- K_1 系統常數, λ 光線的波長,
  $NA = 2\, r_o / D$, 數值孔徑

Exercise 1, $K_1 = 0.6$

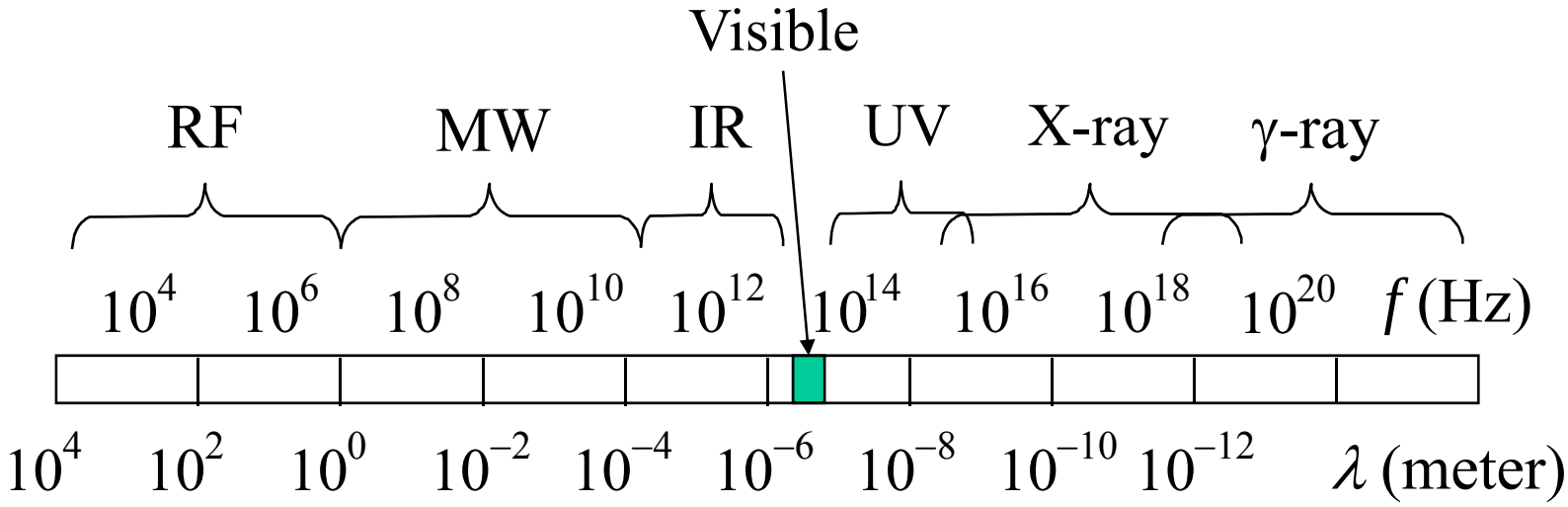
$$R = \frac{K_1 \lambda}{NA}$$

	λ	NA	R
G-line	**436 nm**	**0.60**	**___ μm**
I-line	**365 nm**	**0.60**	**___ μm**
DUV	**248 nm**	**0.60**	**___ μm**
	193 nm	**0.60**	**___ μm**

To Improve Resolution

- 增加NA
  - 大的透鏡,可能太昂貴及不切實際
  - 減少景深但導致製程的困難度
- 減短波長
  - 需要發展光源,光阻及設備
  - 限制因素為了減短波長
  - UV to DUV, to EUV, and to X-Ray
- 減小K_1
  - 相位移光罩(Phase shift mask)

Wavelength and Frequency of Electromagnetic Wave



RF: Radio frequency; MW: Microwave; IR: infrared; and UV: ultraviolet

Wavelength and Frequency of Electromagnetic Wave

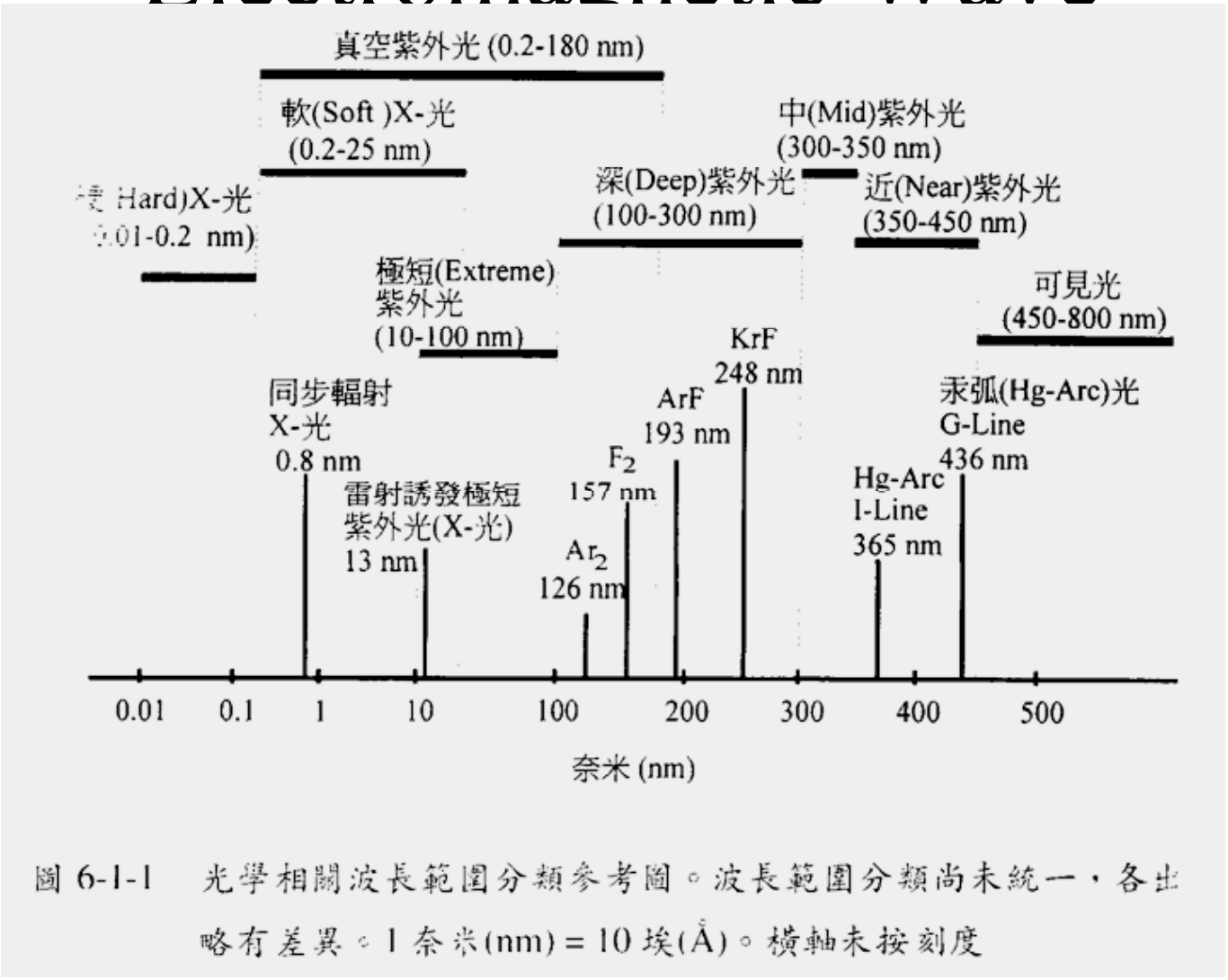


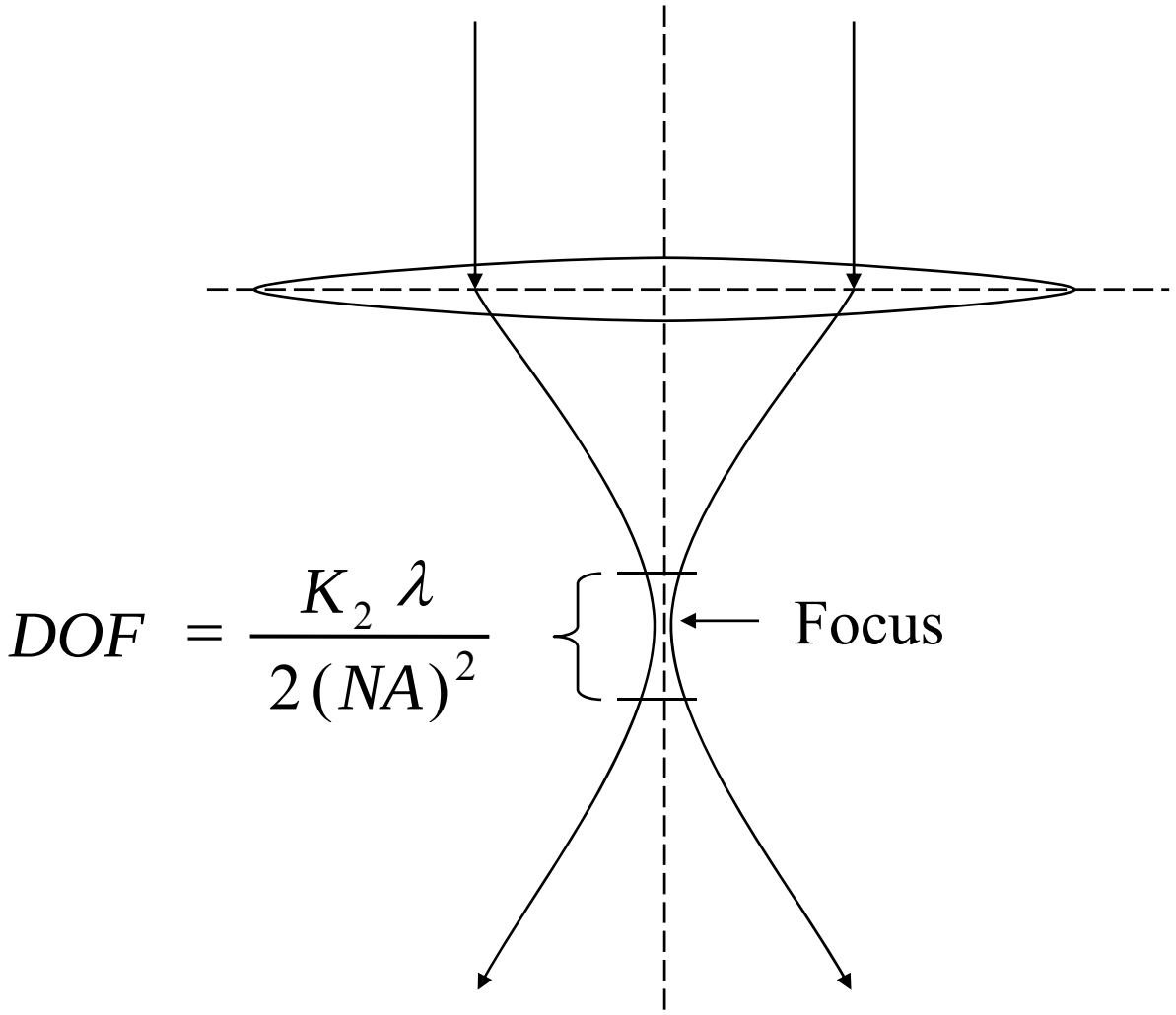
圖 6-1-1　光學相關波長範圍分類參考圖。波長範圍分類尚未統一，各出略有差異。1 奈米(nm) = 10 埃(Å)。橫軸未按刻度

Depth of focus

- 光在焦距上且可使投射影像達到好的解析度的範圍
- 景深可表示為:

$$DOF = \frac{K_2 \lambda}{2(NA)^2}$$

Depth of Focus



Exercise 2, $K_2 = 0.6$

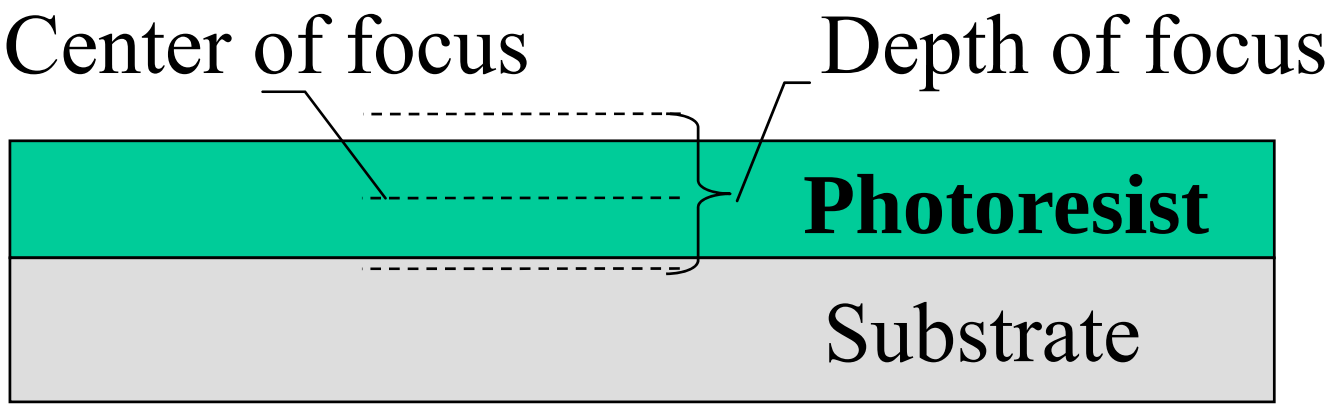
$$DOF = \frac{K_2 \lambda}{2(NA)^2}$$

	λ	NA	DOF
G-line	**436 nm**	**0.60**	**___ μm**
I-line	**365 nm**	**0.60**	**___ μm**
DUV	**248 nm**	**0.60**	**___ μm**
	193 nm	**0.60**	**___ μm**

Depth of Focus

- 較小的數值孔徑, 較大的景深
  - 傻瓜向機的鏡頭都很小
  - 幾乎所有的東西都在焦距內
  - 較差的解析度
- 寧願減短波長也不願增加數值孔徑去改善解析度
- 高解析度,低景深
- 焦距在光阻層的中央

Focus on the Mid-Plain to Optimize the Resolution



Surface Planarization Requirement

- 高解析度需要
  - 短的 λ
  - 大的 *NA*.
- 降低 *DOF*
- 晶圓表面需要高度平坦化(planarized).
- 圖案化需要應用化學機械研磨(CMP)

I-line and DUV

- 水銀 i-line, 365 nm
  - 通常運用於0.35 μm 微影技術
- DUV 氟化氪(KrF) 準分子雷射, 248 nm
  - 0.25 μm, 0.18 μm and 0.13 μm lithography
- 氟化氬(ArF)準分子雷射,193 nm
  - Application: < 0.13 μm
- 氟(F_2) 準分子雷射,157 nm
  - 仍在研究發展中, < 0.10 μm application

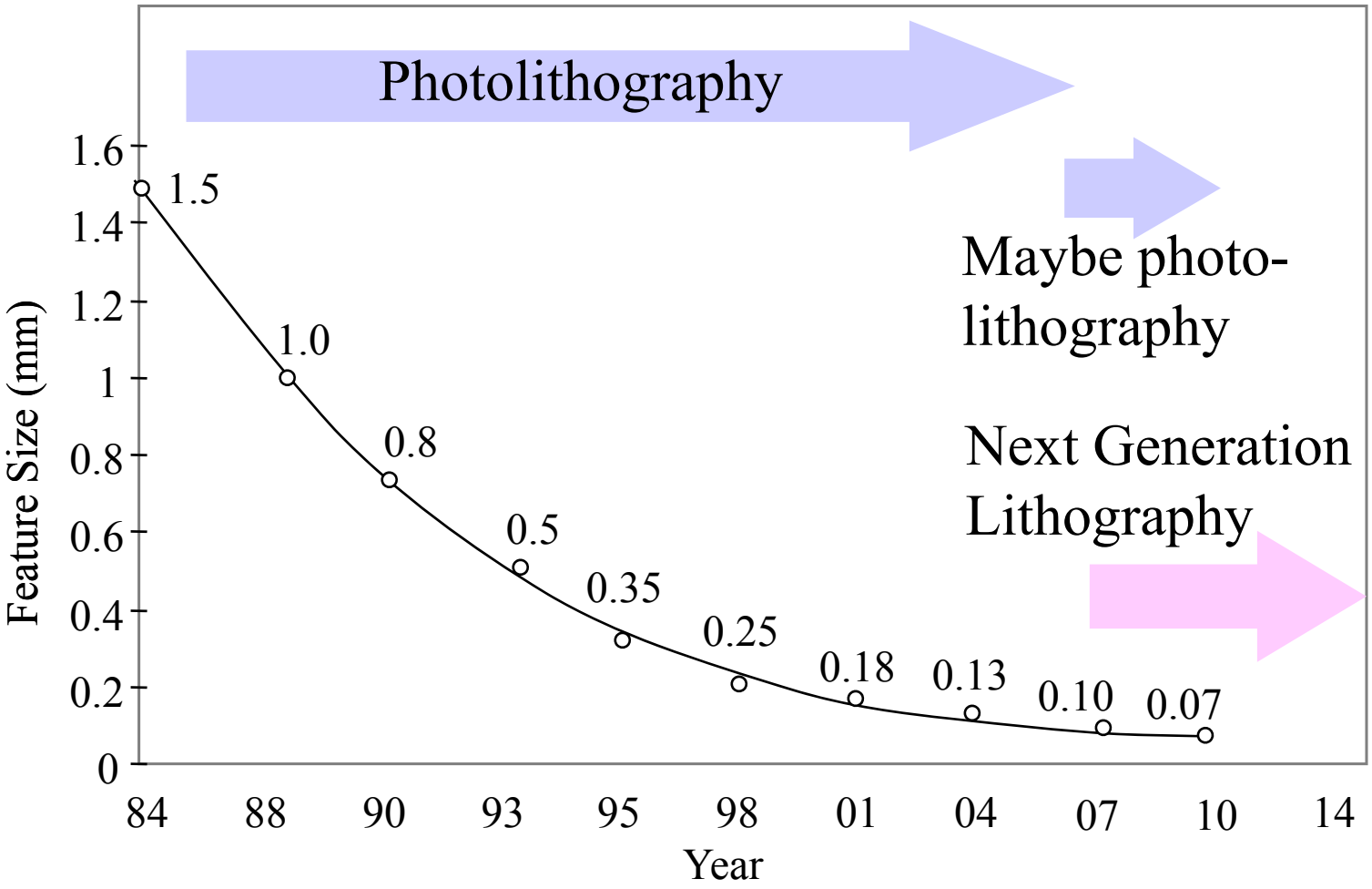
I-line and DUV

- 矽玻璃(SiO_2)強力吸收紫外線當波長 $\lambda <$ 180 nm
- 二氧化矽透鏡及光罩無法使用
- 157 nm F_2 雷射微影技術
  - 含低OH濃度的熔合二氧化矽,摻雜氟的二氧化矽以及氟化鈣(CaF_2)
  - 加上相位移光罩, 0.035 μm都成為可能
- 更延遲下一世代微影技術(next generation lithography ,NGL)

Next Generation Lithography (NGL)

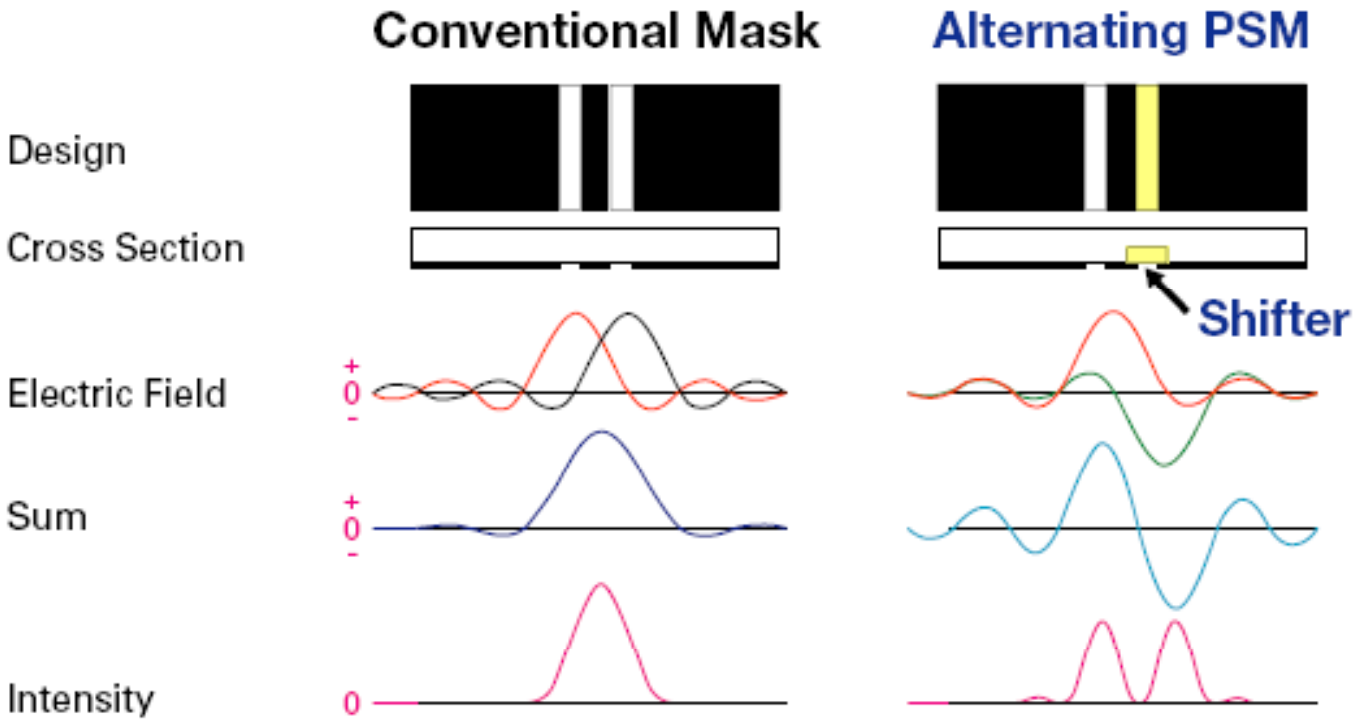
- 極紫外線(EUV)微影技術
- X-Ray lithography
- 電子束微影系統Electron beam (E-beam) lithography

Future Trends

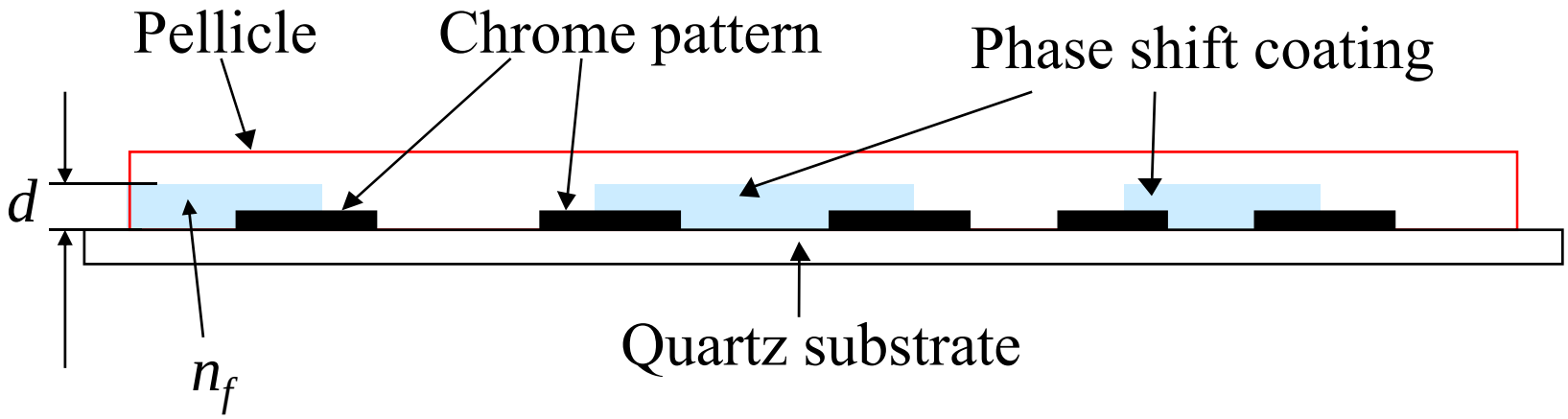


相位移光罩(phase shift mask)

此方法主要由IBM的M. D. Levenson等人在1982年提出，特色是只需稍微修改一般的光罩，就能使曝光圖形的線寬縮小。其概念很簡單，就是在傳統光罩的圖形上，選擇性地在透光區加上透明但能使光束相位反轉180°的反向層，用此光罩來進行微影製程，可使曝光系統之解析能力大增


Conventional Mask
Alternating PSM
Design
Cross Section
Shifter
Electric Field
+
0
-
Sum
+
0
-
Intensity
0

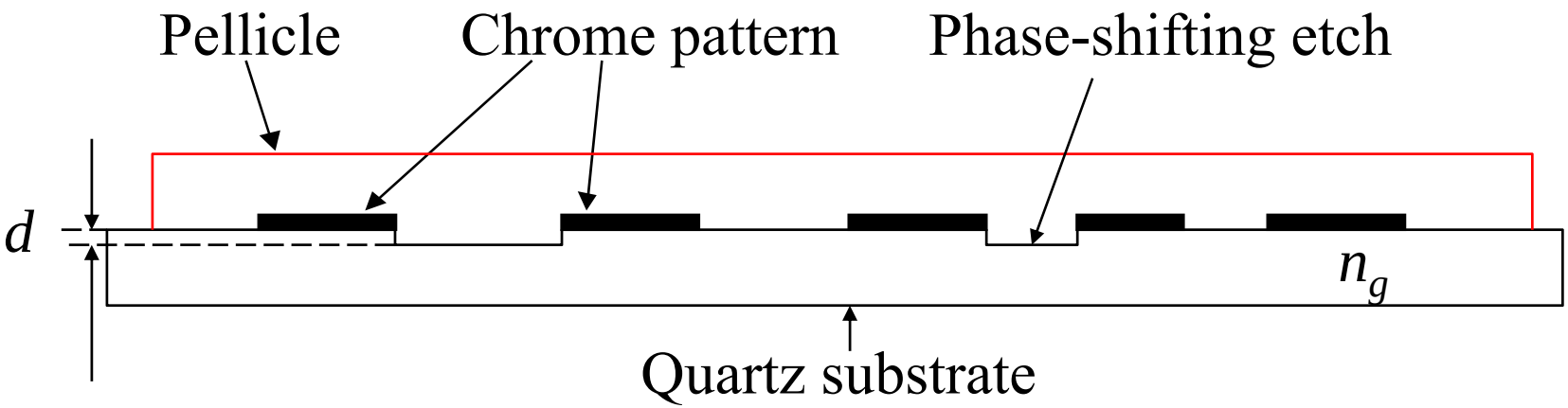
Phase Shift Mask



$$d(n_f - 1) = \lambda/2$$

n_f : Refractive index of phase shift coating

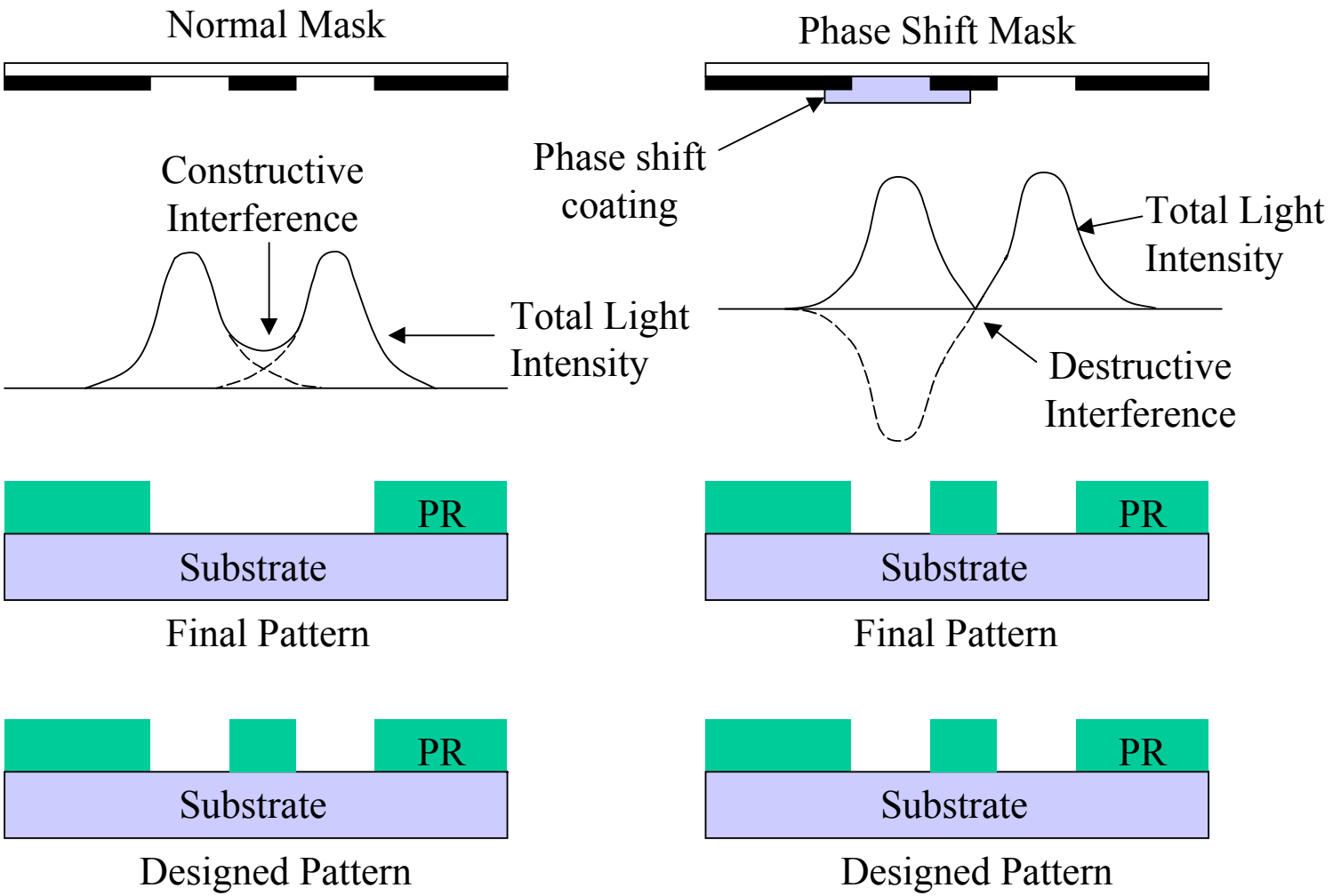
Phase Shift Mask



$$d(n_g - 1) = \lambda/2$$

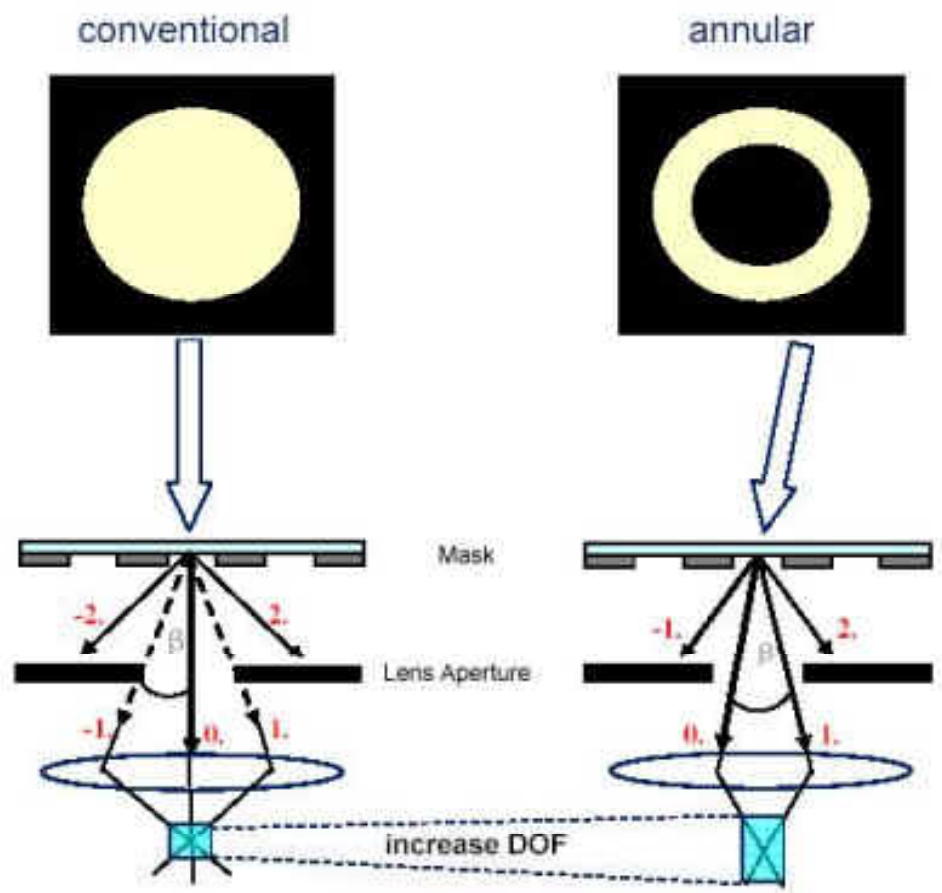
n_g: refractive index of the quartz substrate

Phase Shift Mask Patterning



離軸照明(off-axis illumination)

經由光罩而散射出來的光束，繞射角度相當大，透鏡的數值孔徑必須夠大，才能充分收集這些帶有光罩圖形資料的光束，然而數值孔徑增加會使聚焦深度減少，反而不利於量產。 如果我們能適當地安排使入射光與光罩平面夾一角度，第零階繞射光不再成垂直入射，聚焦深度便可增加，相當於在相同的數值孔徑下提高解析度。



左圖爲使用傳統光罩的三光束成像系統；右圖爲利用環形光罩產生的離軸照

FIGURE 3. Comparison of conventional illumination source to several types of off-axis illumination sources. Note that the black areas are opaque, and the other areas are transparent.

光學鄰近修正術
optical proximity correction

可將現有的光源應用在更小線寬的製程上。當線寬尺寸逼近光波長時，光線穿過光罩後會產生繞射，這些繞射光疊加的結果會與光罩上的圖形相去甚遠，曝光後的圖形因而嚴重失真。

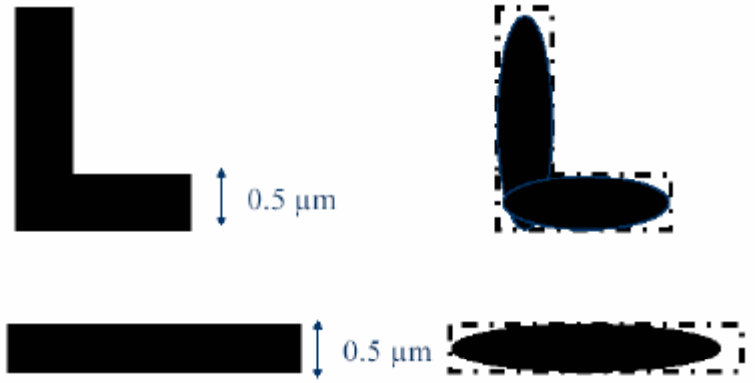
光學鄰近修正術便是將繞射的效應考慮進去，為了補償曝光後圖形的失真，藉由修改光罩上的圖形，使產生的繞射光在疊加後能得到符合實際要求的圖形與線寬。

Resolution Enhancement Techniques (I)

Optical proximity correction (OPC)

OPC uses modified shapes of adjacent subresolution geometry to improve imaging capability

Figure on the mask **Pattern on the wafer**



When the feature size is smaller than the resolution, the pattern will be distorted in several ways:

- **Line width variation**
- **Corner rounding**
- **Line shortening**

Modify the Mask based on rules or model

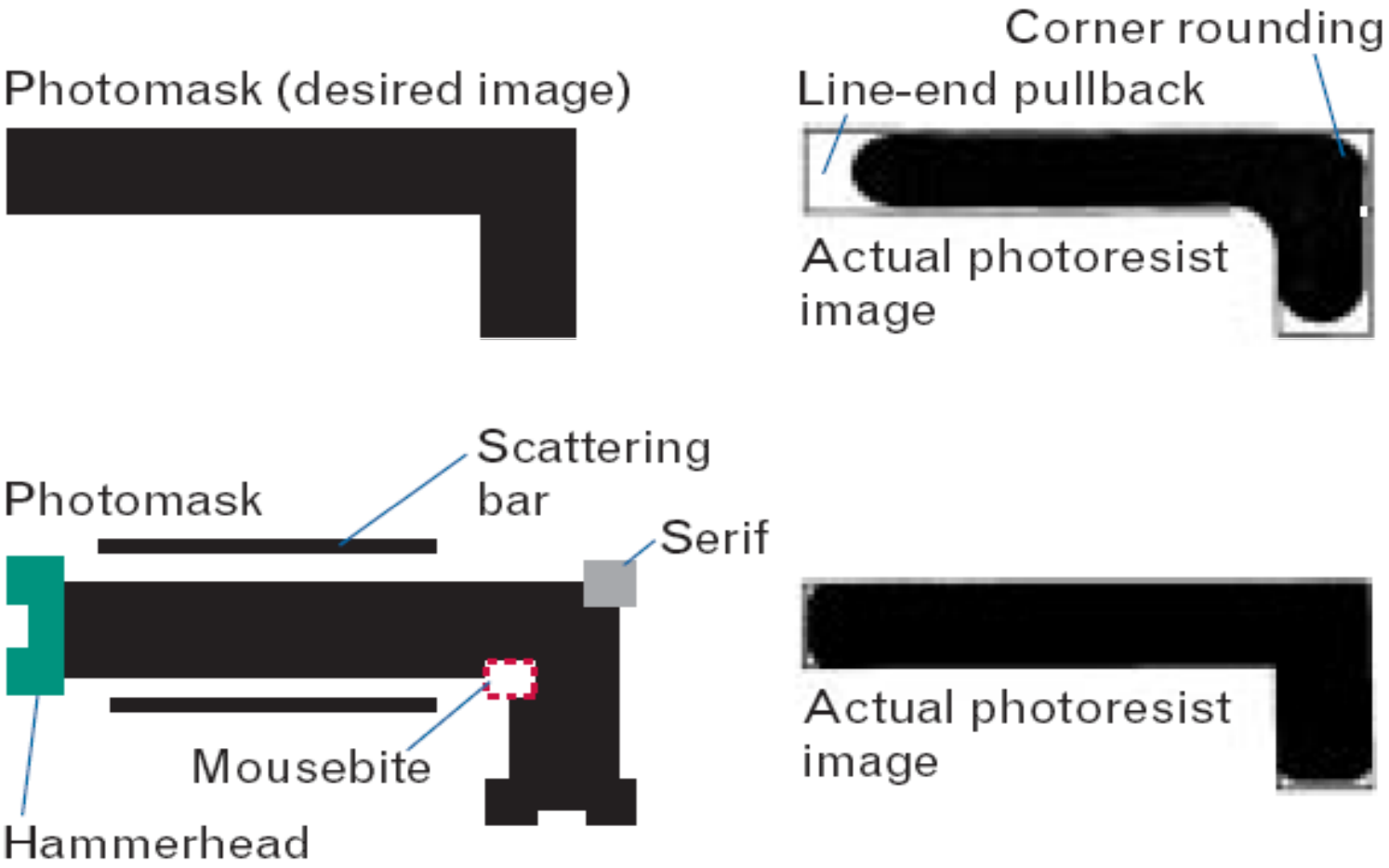
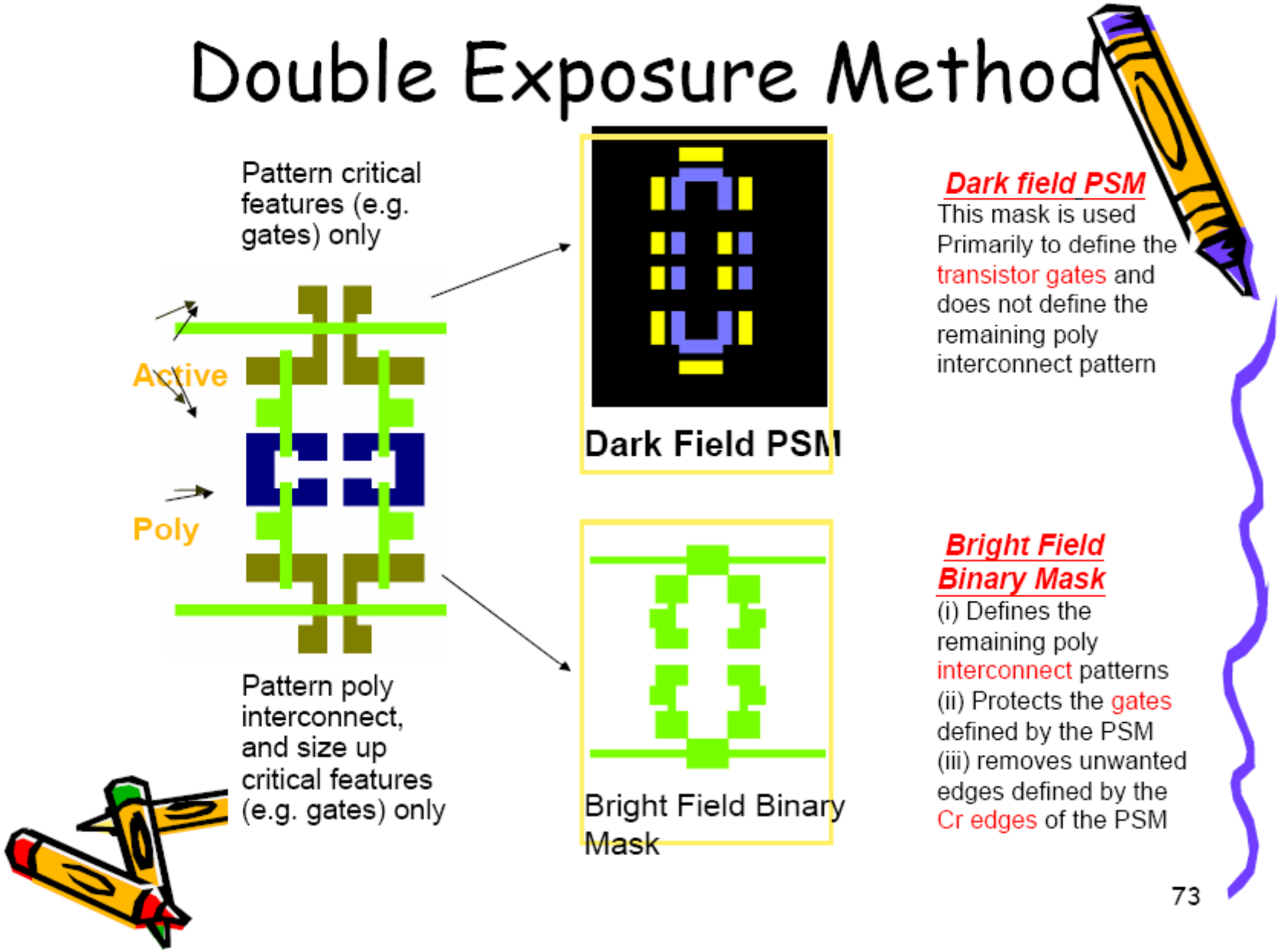
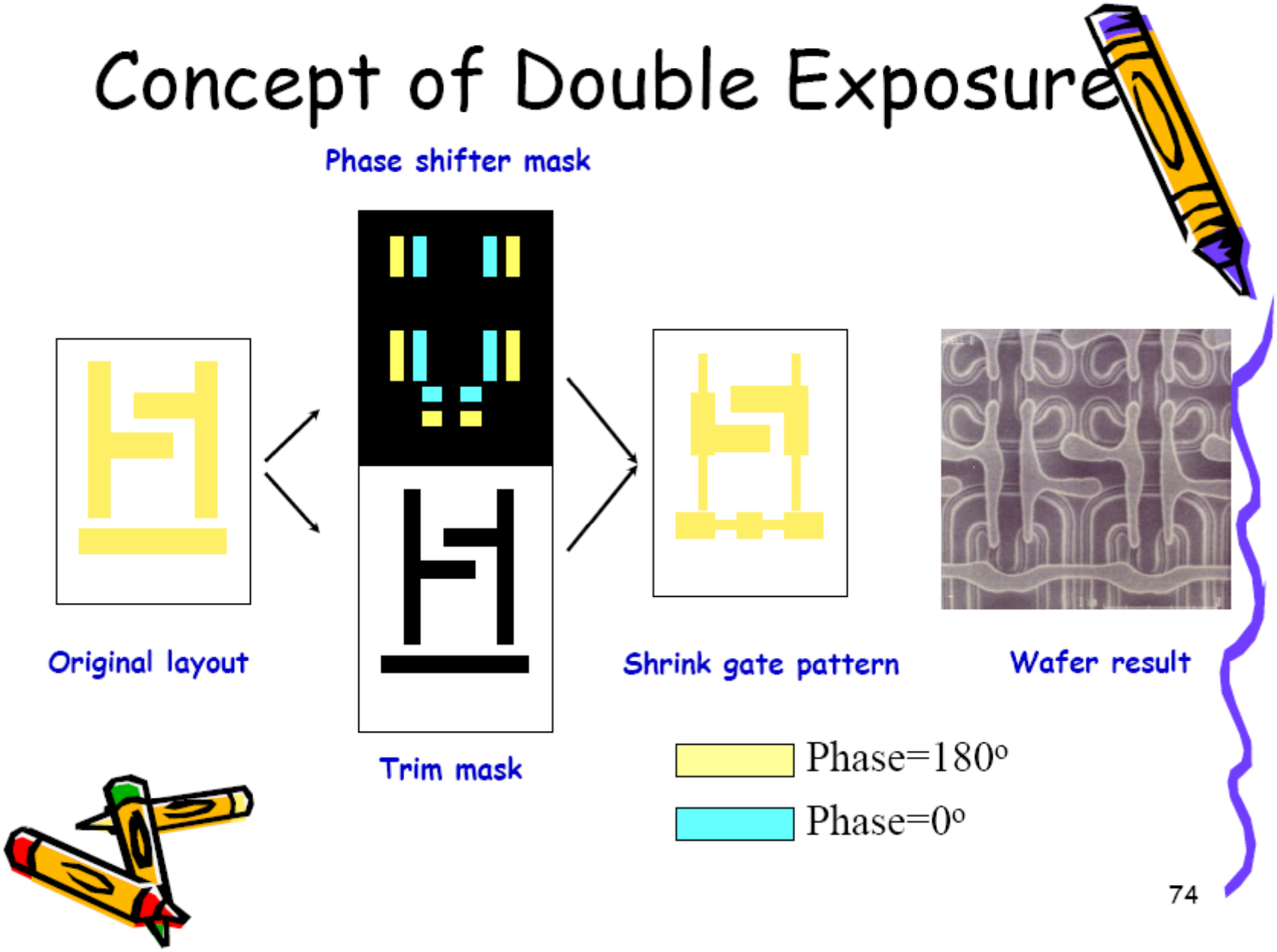


FIGURE 2. Schematic diagram of optical proximity correction. The spatial-frequency effect distorts the image patterned on the photoresist by rounding sharp corner features and shortening narrow line ends. The addition of

Double Exposure Method



Concept of Double Exposure



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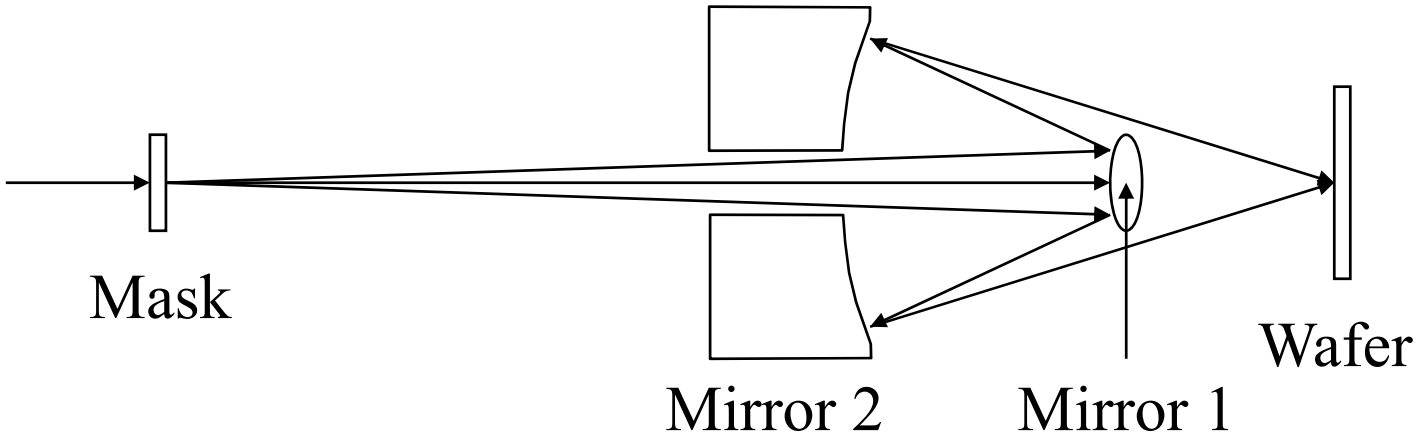
Future Trends

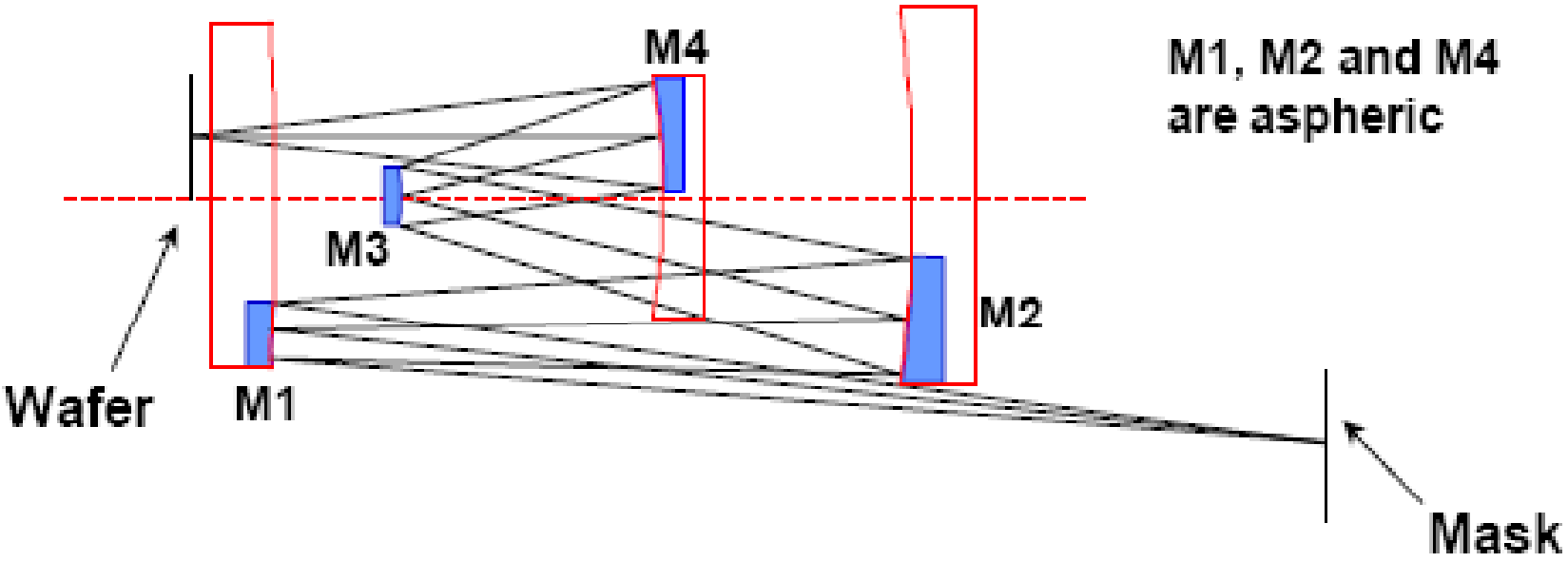
- Even shorter wavelength
  - 193 nm
  - 157 nm
    - Silicate glass absorbs UV light when $\lambda < 180$ nm
    - CaF_2 optical system
- Immersion lithography
- Next generation lithography (NGL)
  - Extreme UV (EVU)
  - Electron Beam
  - X-ray (?)

EUV

- λ = 10 to 14 nm
- Higher resolution
- Mirror based
- Projected application ~ 2010
- 0.1 μm and beyond

EUV Lithography





"engineering test stand," so it is called the ETS camera.

Figure 4: Schematic diagram of the 4-mirror ETS camera

•X-ray Lithography (XLR)

•X-ray (1nm) generated by a synchrotron storage ring is used as the energy source

•as most materials have low transparency at $\lambda \sim 1$nm, the mask substrate must be a thin membrane (1-2μm thick). The pattern itself is defined in a thin (~0.5 μm), relative high-atomic-number materials such as tungsen and gold.

Advantages:

•High resolution (100 nm or better) and high depth of focus

•No reflection from the substrate to create standing wave

Disadvantages:

•Complex and expensive XRL system

•Complex mask fabrication

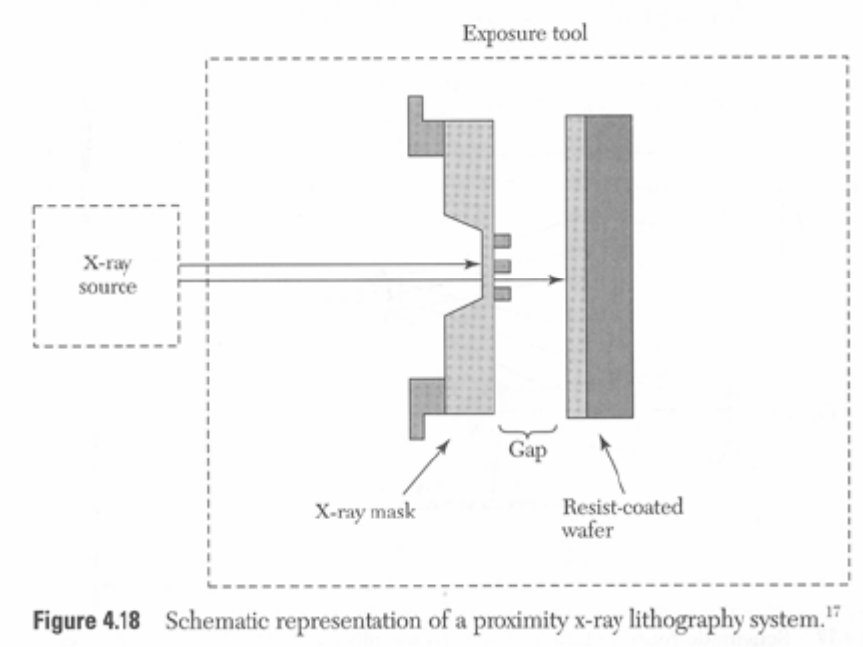
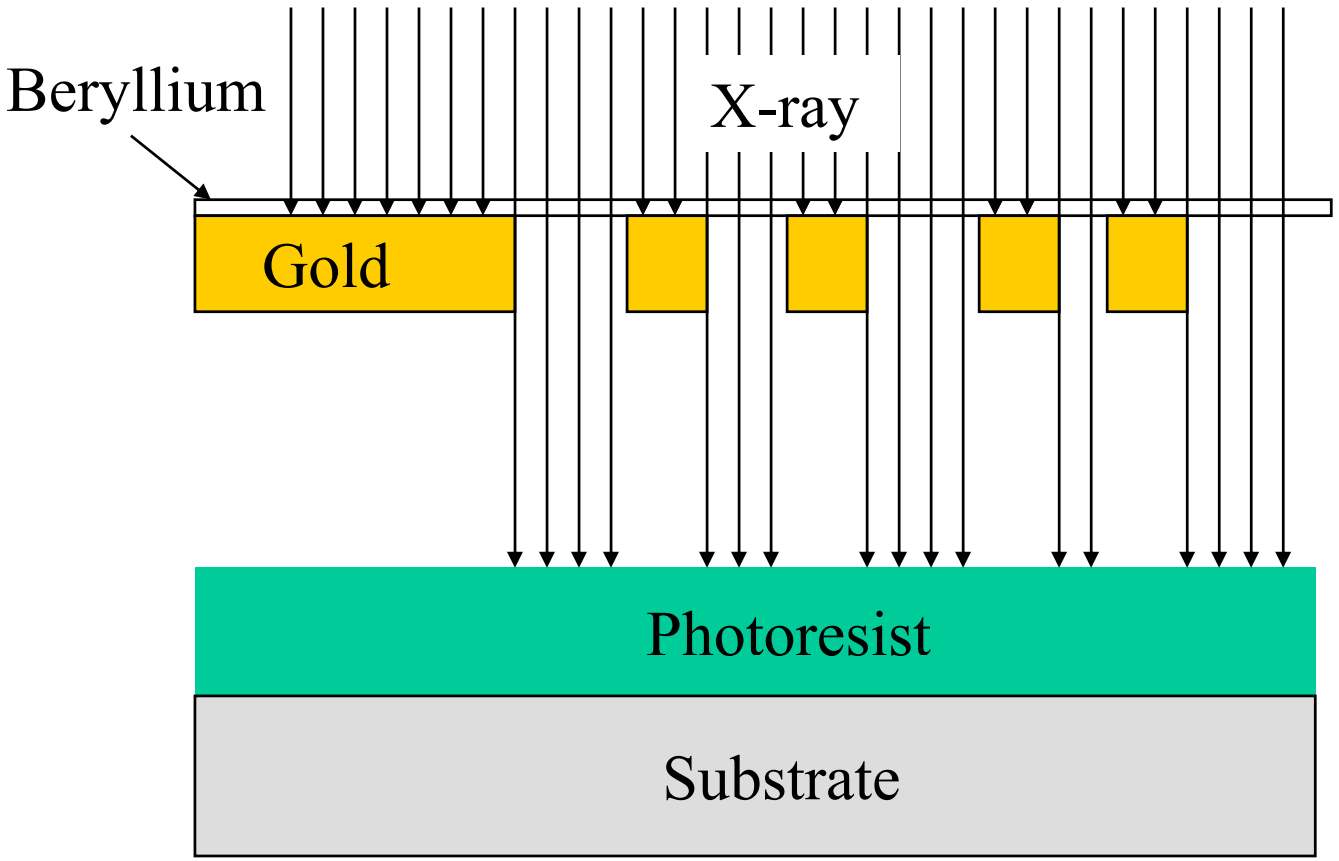


Figure 4.18 Schematic representation of a proximity x-ray lithography system.[17]

X-ray Printing



Optical Mask and X-ray Mask

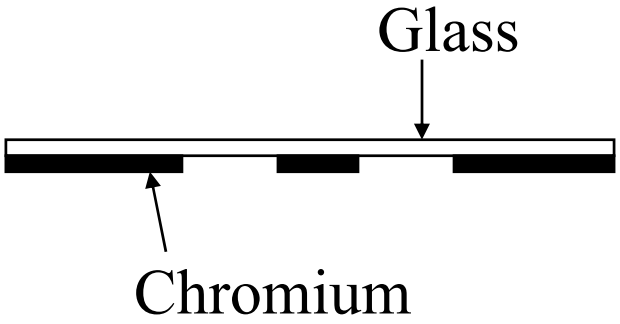
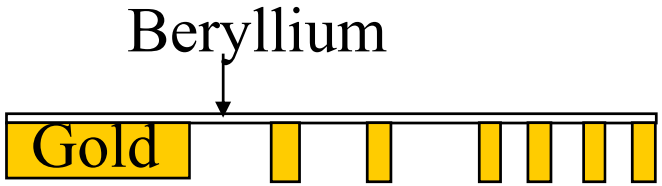


Photo Mask

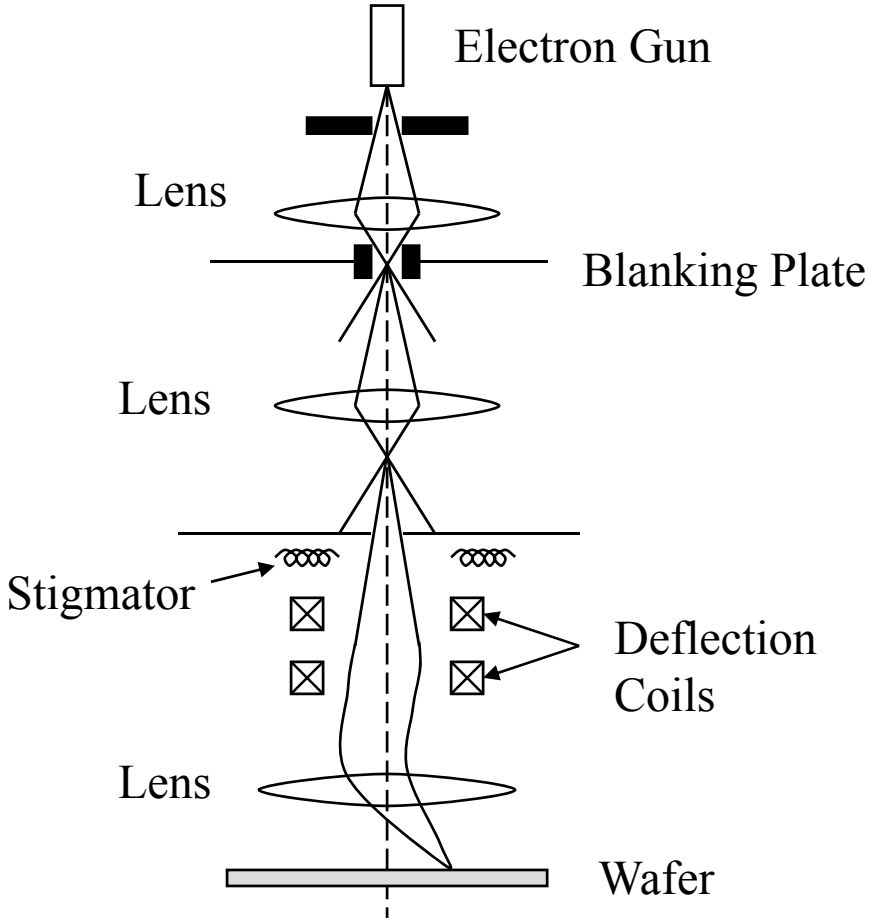


X-ray Mask

E-Beam

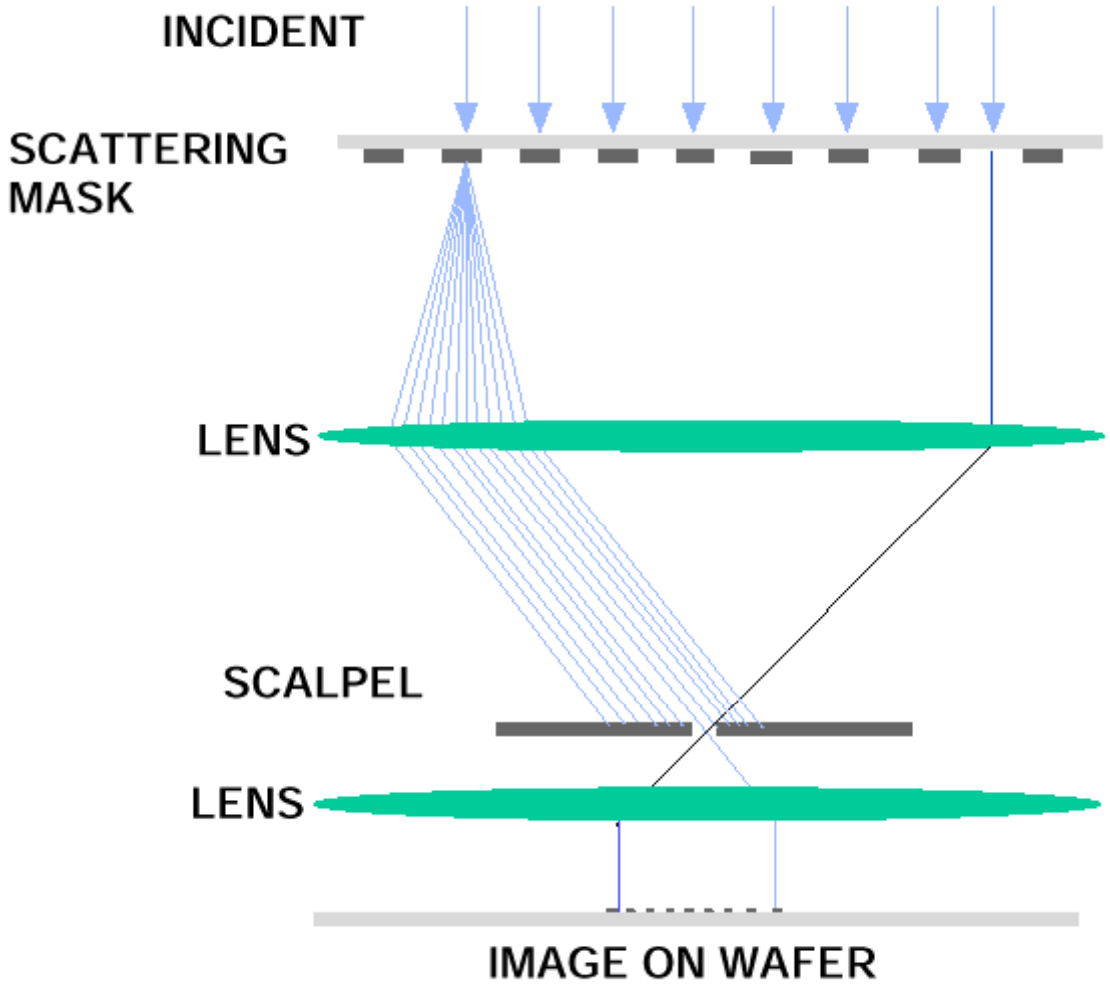
- 運用於製作光罩及倍縮光罩(reticles)
- 達到最小尺寸：0.014 μm
- 直接寫入,不需光罩
  - 低生產量
- 有限角度散射投影式電子束微影技術 (SCALPEL)
  - Tool development
  - Reticle making
  - Resist development

Electron Beam Lithography System

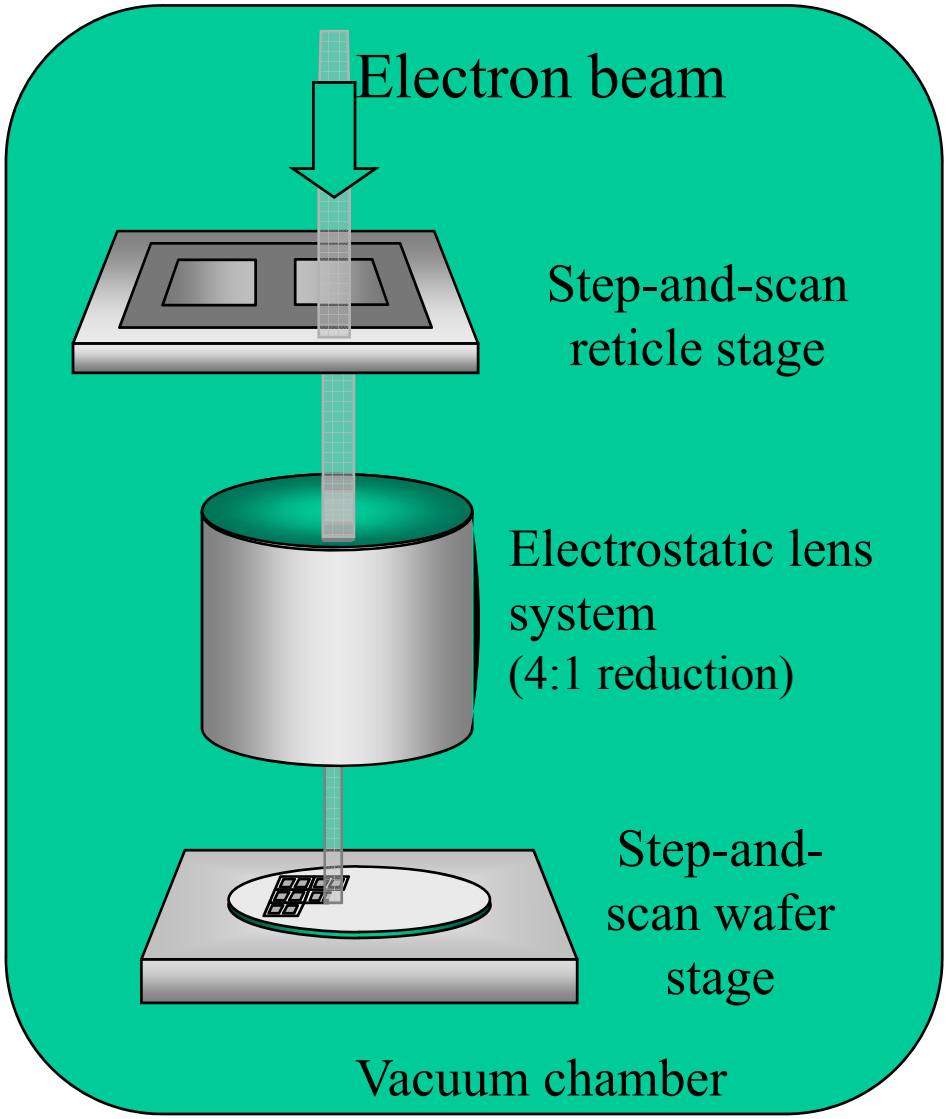


SCALPEL

Scattering with Angular Limitation Projection Electron Lithography



Concept of SCALPEL

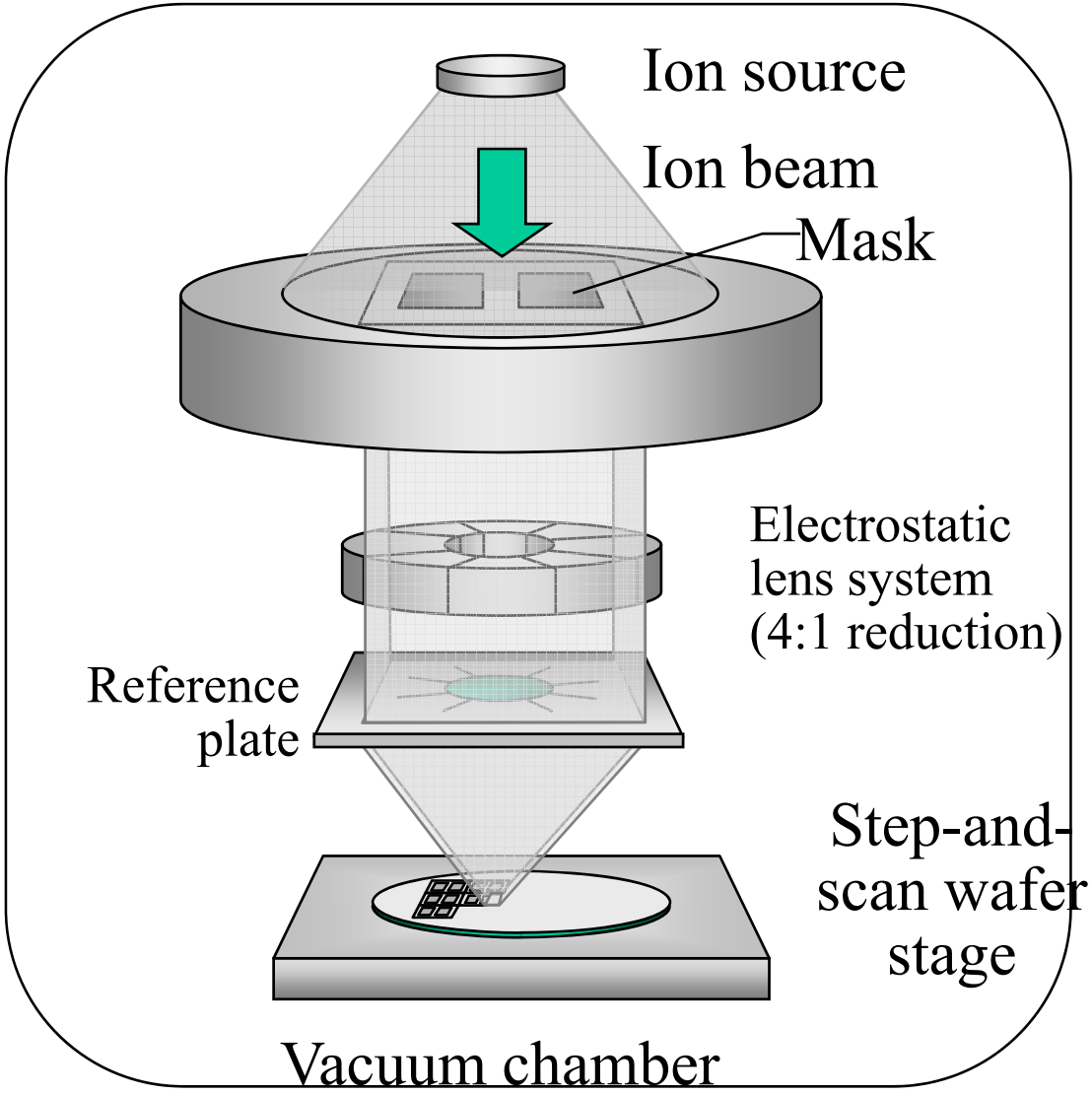


Redrawn from International SEMATECH's Next Generation Lithography Workshop Brochure

Ion Beam Lithography

- 可達更高的解析度
  - 直接寫入及投影式光阻的曝光
  - 直接作離子佈植及進行離子束濺射(sputtering patterned)的圖案蝕刻可節省一些步驟
- 連續寫入,低生產量
- 不可能作為大量生產
- 光罩及倍縮光罩的修補
- IC元件缺陷偵測及修補

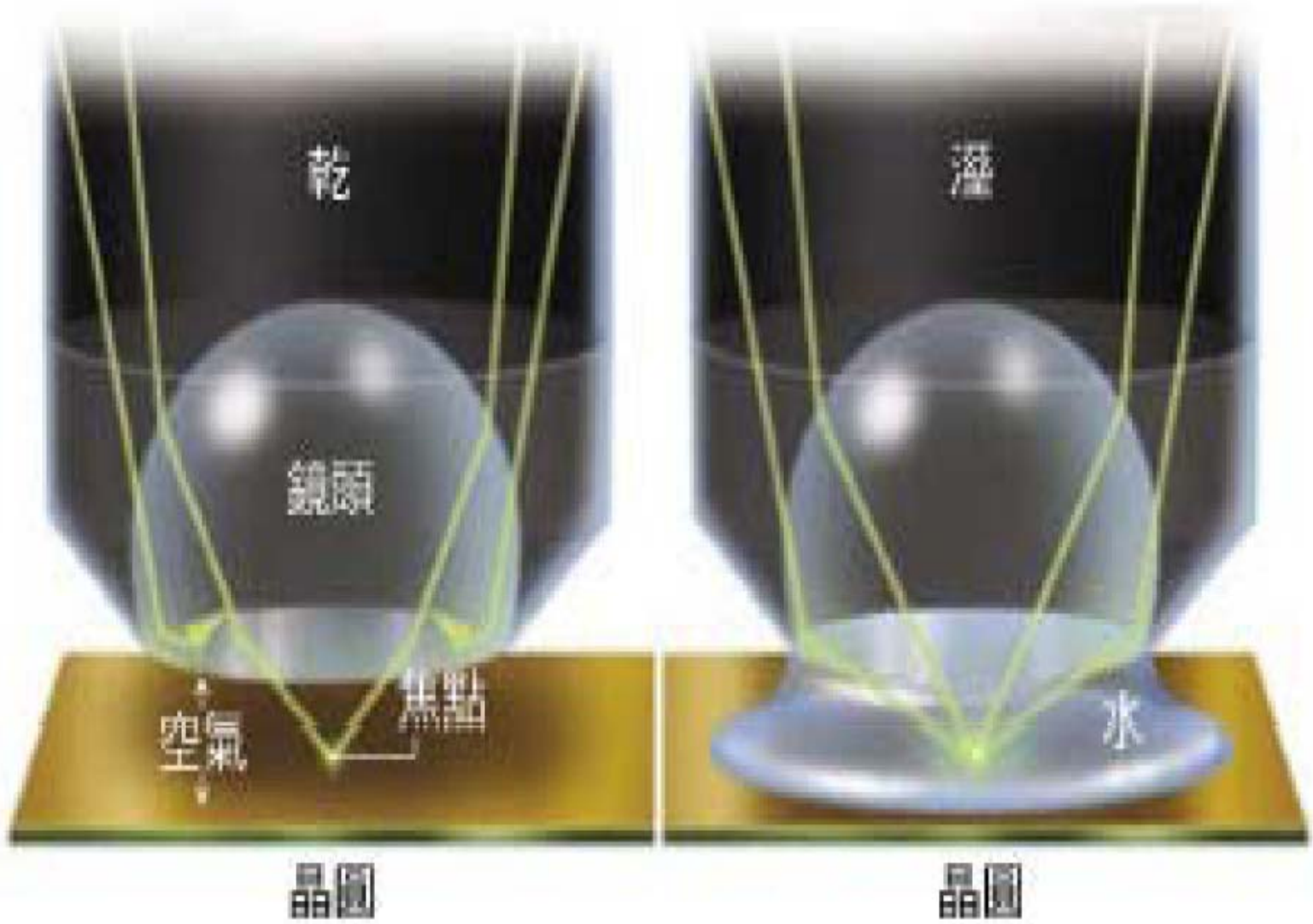
Ion Projection Lithography



Redrawn from International SEMATECH's Next Generation Lithography Workshop Brochure

浸潤式微影
immersion lithography

- 在透鏡與光阻間浸入折射率大於1的液體
- 可以減少波長，增進解像度
- 純水折射率=1.44
- 193nm的光有134nm的效果
- 如果在純水加入適當物質可以提升折射率
- 所以193nm的光可以製造40nm以下的線幅
- 水對157nm的光不透明


乾
鏡頭
空氣
焦點
晶圓
濕
水
晶圓

- 193 nm resist platforms release relatively low volumes of gas during exposure.
- The reaction of water with 193 nm photoresist is minimal and can be reduced through modification of resist materials.
- Water is transparent to below 0.05 cm-1 at 193 nm.
- Water is an existing component of wafer processing, limiting the critical concerns of wetting, cleaning and drying.
- Few alternative optical choices now exist.

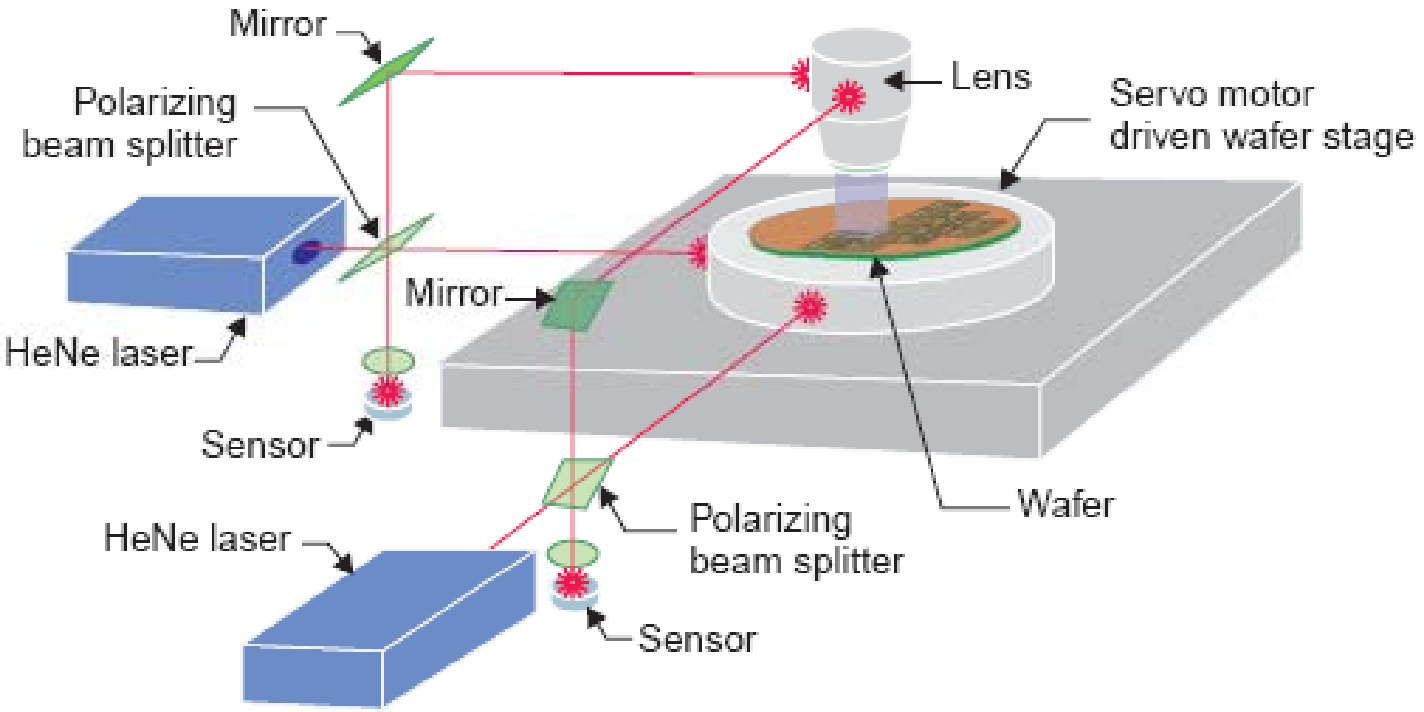


Figure 4. Stepping exposure system stage control

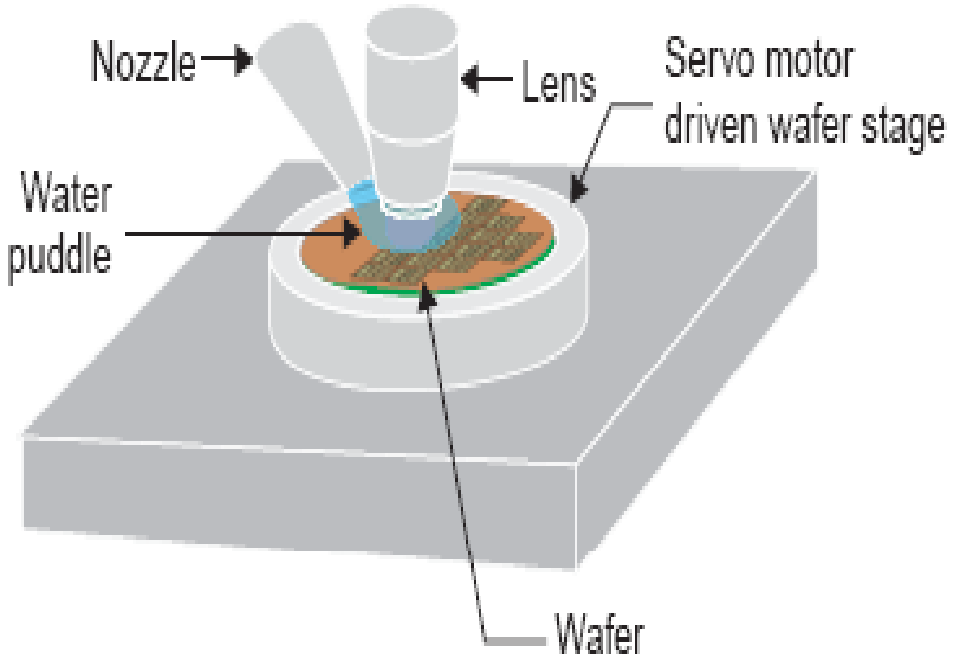
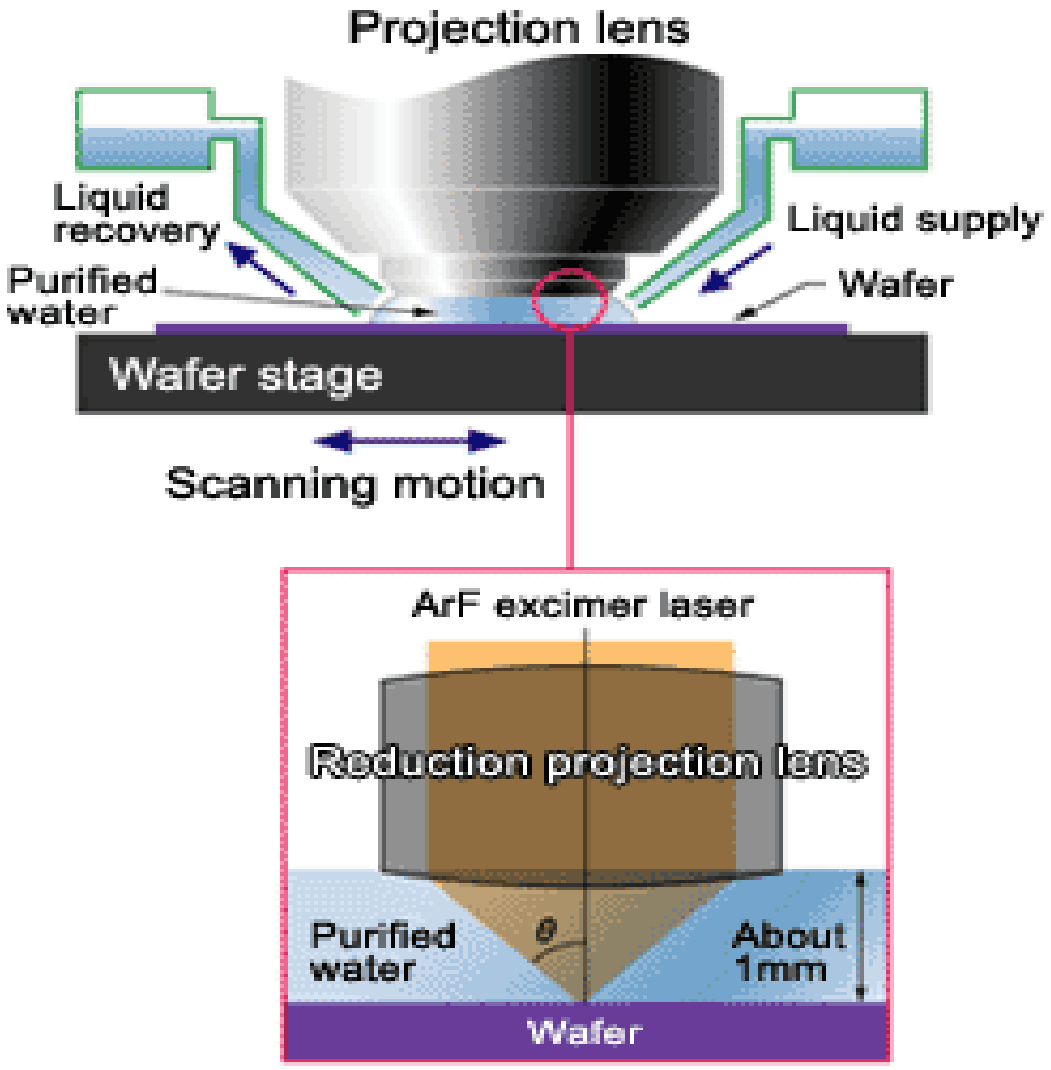
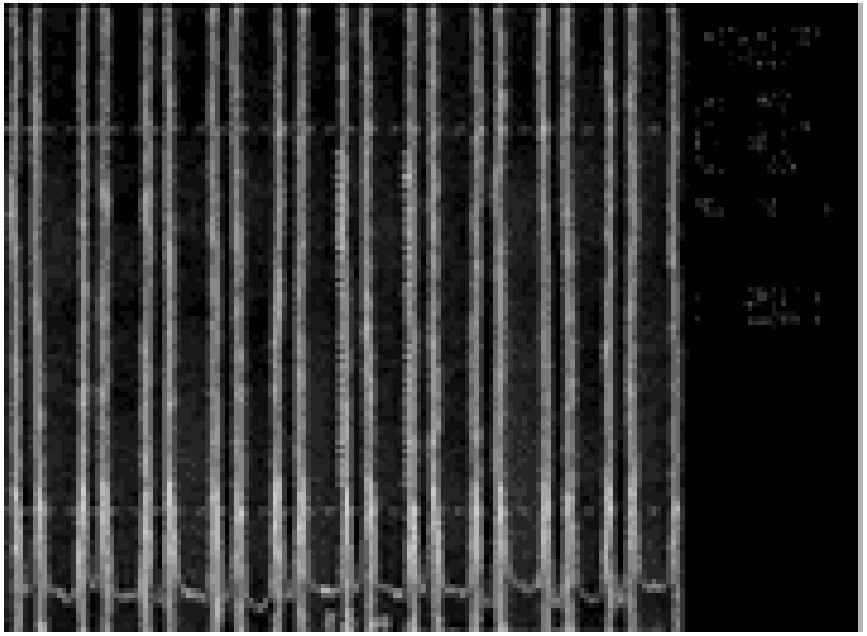
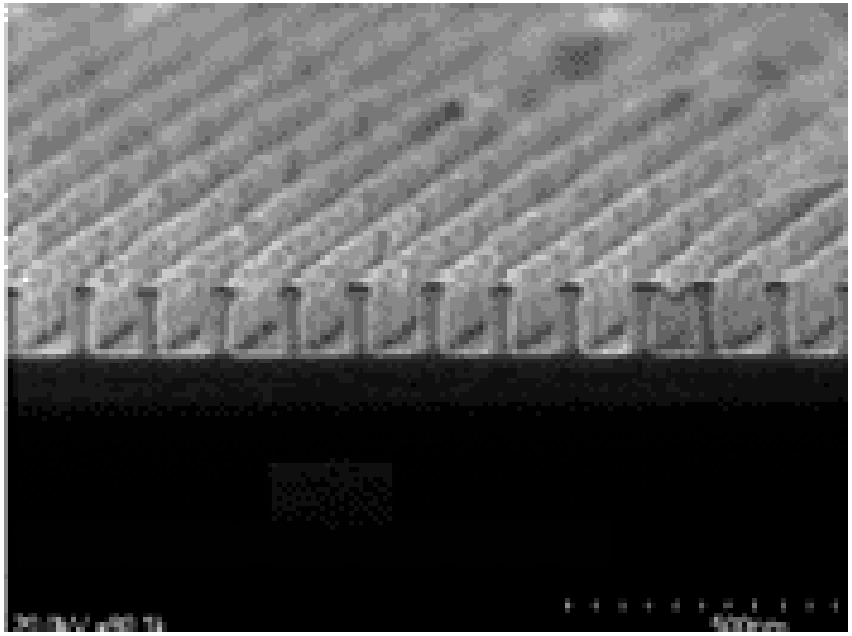


Figure 5. Immersion lithography. Stage control omitted for clarity.


Projection lens
Liquid recovery
Liquid supply
Purified water
Wafer
Wafer stage
Scanning motion
ArF excimer laser
Reduction projection lens
Purified water
θ
About 1mm
Wafer





- Immersion Lithography Results
  65nm line-and-space pattern (joint test with Tokyo Ohka Kogyo)

Safety

- 化學Chemical
- 機械Mechanical
- 電氣Electrical
- 輻射Radiation

Chemical Safety

- 濕式清洗
  - 硫酸(Sulfuric acid,H_2SO_4)：具腐蝕性
  - 過氧化氫(Hydrogen peroxide,H_2O_2)：強氧化劑
- 二甲苯Xylene (負光阻的溶劑與顯影劑)：易燃且具爆炸性
- HMDS (底漆層)：易燃且具爆炸性
- TMAH (正光阻顯影溶劑)：有毒且具腐蝕性

Chemical Safety

- 水銀Mercury (Hg , 紫外線光源)蒸發
  - 劇毒
- 氯Chlorine (Cl_2, 準分子雷射)
  - 有毒且具腐蝕性
- 氟Fluorine (F_2,準分子雷射)
  - 有毒且具腐蝕性

Mechanical Safety

- 可移動部分
- 高熱表面
- 高壓燈管

Electrical Safety

- 高壓電力供應
- 電源關閉
- 靜電充電器接地
- 標示及鎖上

Radiation Safety

- 紫外線可打斷化學鍵
- 有機分子具常鍵結構
- 紫外線可用來消毒殺菌
- 直視紫外線光源會造成眼睛傷害
- 必須使用紫外線保護鏡