微細加工

Micro-Machining

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Characteristics of Etching Techniques

- Selectivity
  - Etching method removes a specific material but does not (or only slightly) remove other materials
- Directional Property
  - Isotropic: etching speed is the same in every direction.
  - Anisotropic: etching speed is NOT the same in every direction.

Etching Mechanisms

- Chemical Wet Etching
  - Dipping the substrate into an etching bath or spraying it with the etching solution.
  - Etching solution is acidic or alkaline to dissolve the material to be removed.
- Dry Etching
  - Expose the substrate to an ionized gas.
  - Chemical or physical interaction occur between the ions in the gas and the atoms of the substrate.

MEMS材料與常用之蝕刻液

- Si (Single-Crystal Silicon, Polysilicon)
  - Anisotropic etching: KOH (Potassium Hydroxide), EDP (Ethylene-Diamine Pyrocatecol), TMAH
  - Isotropic etching: HNA etching system, hydrofluoric (HF), nitric (HNO_3), acetic acid (CH_3COOH)
- SiO_2 (Thermal SiO_2, LTO, PSG)
  - Release process using 49% HF
  - Oxide patterning using buffered HF (28 ml 49% HF, 170 ml H_2O, 113 g NH_4F), also know as Buffered Oxide Etch (BOE)
- Quartz (Crystalline SiO_2): Anisotropic etching in heated HF and ammonium fluoride (NH_4F) solution
- SOG: dissolved in $HCl:HF:H_2O$

Isotropic Etching

- Chemical wet etching for amorphous or polycrystalline (ex. polysilicon) is always isotropic.
- Cavities with rounded off edges (undesired in design).
- Resist is undercut.
- Limited in deep forming.
- Dimension control is difficult.
- Useful in surface micromachining.

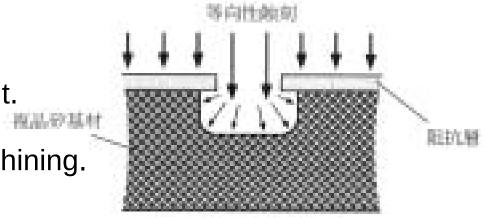


圖 4.6　等向性化學濕蝕刻。

Anisotropic Etching

- Etching speed depends on the crystal’s orientation in single-crystal silicon.
- Typical etching rate : {110}>{100}>>{111}
- Precisely structured in 3D.

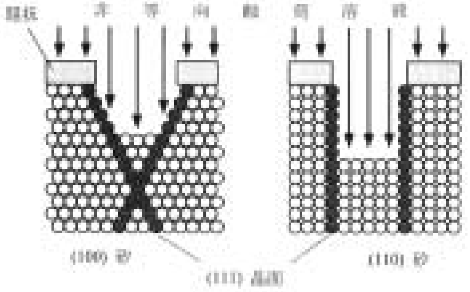


圖 4.8　單晶矽的非等向蝕刻。

矽非等向蝕刻液的種類

- 有機溶液：TMAH、聯氨(Hydrazine)及EDP
  - 聯氨(Hydrazine)及EDP具毒性且不穩定
  - TMAH與IC製程相容，可以二氧化矽作為蝕刻阻擋層(etching mask)，無毒，但蝕刻速率較低
- 鹼液：KOH, NaOH, LiOH, CsOH, NH_4OH,並可添加異丙醇(IPA)等
  - KOH低毒性、較佳的蝕刻面，故常被使用，但鉀離子會污染IC製程
- 影響蝕刻速率除了晶格方向與蝕刻液的種類外，尚包括溫度、濃度、攪拌形式、滲雜種類、表面缺陷、薄膜應力、表面雜質的殘留、氣泡、PH值等

非等向蝕刻液的比較

	TMAH	EDP	KOH
操作及處理	易	難	易
毒性	無	有	無
矽的蝕刻速率	～1 μm/min	0.02-1 μm/min	1-2 μm/min
蝕刻面平坦度	多變*	極佳	佳
IC 製程相容性	相容	相容	不相容
硼蝕刻停止	$>10^{20}/cm^3$	$\geqq 5\times 10^{19}/cm^3$	$>10^{20}/cm^3$
其他材料的選擇性	Al**	Ta, Au, Cr, Ag, Cu	N/A
蝕刻阻擋層	Si_3N_4, SiO_2	Si_3N_4, SiO_2	Si_3N_4 SiO_2淺蝕刻*

* etch rate of SiO_2=435 nm/hr at 80°C 30% KOH

溼蝕刻的機制

- 濕蝕刻的機制
  - 蝕刻液由邊界層外傳輸至蝕刻表面
  - 蝕刻液與蝕刻面反應產生生成物
  - 生成物由蝕刻表面傳輸至邊界層外

$$\mathrm{Si} + 2\mathrm{OH}^- \rightarrow \mathrm{Si(OH)}_2^{++} + 4\mathrm{e}^-$$

$$4\mathrm{H}_2\mathrm{O} + 4\mathrm{e}^- \rightarrow 4\mathrm{OH}^- + 2\mathrm{H}_2$$

$$\mathrm{Si(OH)}_2^{++} + 4\mathrm{OH}^- \rightarrow \mathrm{SiO}_2(\mathrm{OH})_2^{--} + 2\mathrm{H}_2\mathrm{O}$$

$$\mathrm{Si} + 2\mathrm{OH}^- + 2\mathrm{H}_2\mathrm{O} \rightarrow \mathrm{SiO}_2(\mathrm{OH})_2^{--} + 2\mathrm{H}_2$$

- 外加攪拌可產生強制對流，增加第一、三道的值量傳遞過程，而第二道過程為化學反應
  - 溫度越高蝕刻速率越高，但蝕刻面粗糙度將變差
  - 固定溫度下存在一蝕刻速率最高的蝕刻液濃度

Silicon Lattice Structure

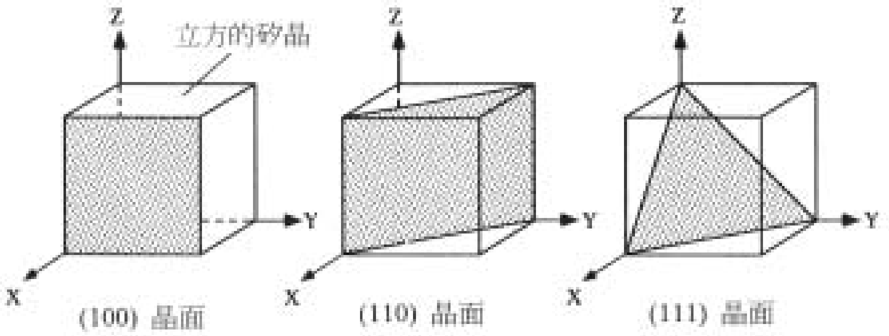
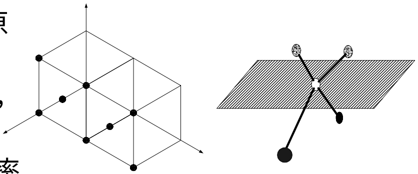


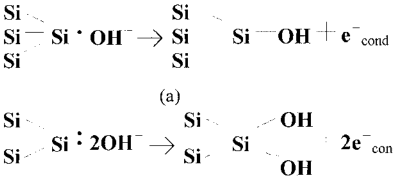
圖 4.7 矽晶格構造之晶面。

晶格鍵結與蝕刻

- {100}與{111}面的共價鍵與懸垂鍵
  - KOH蝕刻時蝕刻液的OH^-與矽原子的懸垂鍵反應
  - {111}有三個共價鍵，強度較高，故蝕刻速率低
  - {100}只有兩個共價鍵，蝕刻速率高
  - 速率R{111}/R{100} = 1:80~1:120



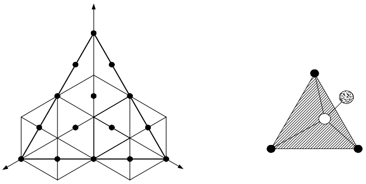
Si atoms on a {100} plane



$$\mathrm{Si_3{-}Si\cdot OH^- \rightarrow Si_3{-}Si{-}OH + e^-_{cond}}$$

(a)

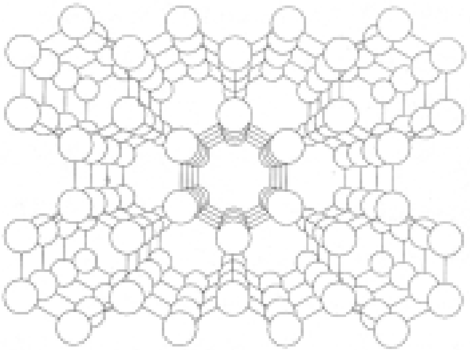
$$\mathrm{Si_2{=}Si : 2OH^- \rightarrow Si_2{=}Si(OH)_2 \; 2e^-_{cond}}$$



Si atoms on a {111} plane

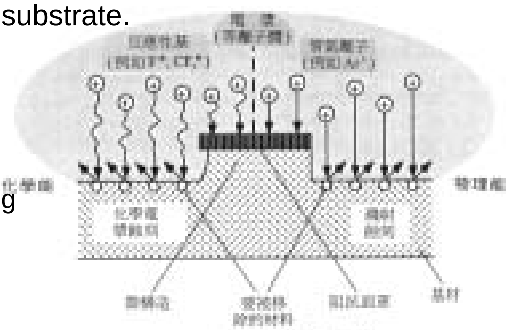
單晶矽的晶格方向與蝕刻速率

- {110}晶面雖然有三個共價鍵，但因晶面的原子排列鬆散，以致蝕刻液對矽原子結構產生穿遂效應(Channeling effect)，造成蝕刻速率較快(Hesketh, 1993)。



Dry Etching

- Expose the substrate to an ionized inert gas (argon, helium, xenon).
- Chemical or physical interaction between the ions in the gas and the atoms of the substrate.
- Three groups:
  - Physical sputter etching (ion beam etching)
  - Chemical plasma etching
  - Combined physical/ chemical etching



Dry Etching

- Physical sputter etching / Ion beam etching
  - Inert ions bombard the substrate fixed to the cathode
  - Anisotropic
  - Selectivity is not guaranteed.
  - Etch rate ~10 nm/min
- Chemical plasma etching
  - Active radical（活性初生基）
  - Isotropic
  - Excellent Selectivity
  - Etch rate ~100 nm/min
- Combined physical chemical etching
  - Reactive Ion Etching (RIE)
  - Etch rate 20~200 nm/min

Reactive Ion Etching

- RIE乃以F, Cl, C, O等組成之氣體電漿，經電和磁場時離子在低壓中加速，以化學與機械撞擊的方式去除材料
- RIE常用之氣體

編號	**基材**	**氣體**
1	Aluminum	CCl_4；BCl_3
2	Silicon	CF_4+O_2；SF_6+O_2；CF_4；CCl_4；$CBrF_3$
3	Silicon dioxide	CF_4+H_2；C_2F_6；C_3F_8；C_4F_8
4	Silicon nitride	CF_4+H_2；CH_2F_6；CH_3F
5	GaAs	CF_2Cl_2；CCl_4；Cl_2
6	InP	CCl_2+O_2；Cl_2

Example of Dry Etching

- Free standing Al structure on a silicon substrate

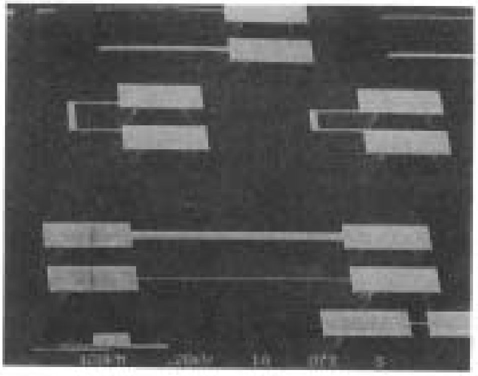


圖 4.11 由電漿蝕刻製程所得之鋁製微構造。感謝 the University of Neuchâtel (Institute of Microtechnology)。

Lift-Off

- Often used for making electrically conductive layers from hard-to-etch metals
- Lithography of PR pattern
- Sputtering structuring material (or CVD)
- Aceton as solvent

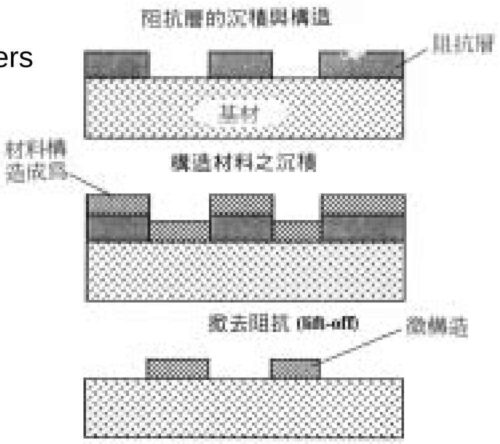


圖 4.12 用爲構成之撤去技術

Typical Application of Lift-Off

- Interdigital capacitor

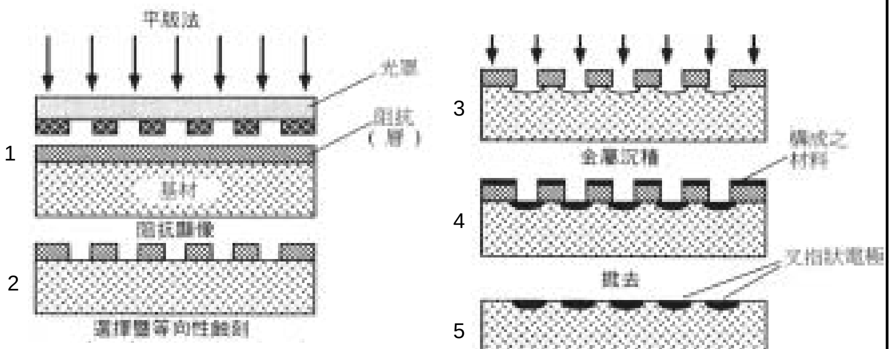
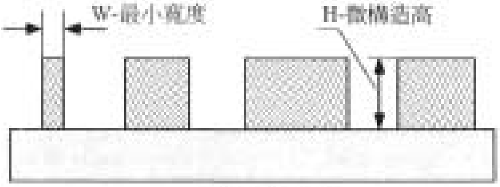


圖 4.13 製造叉指狀陣列電容之撤去技術

Bulk Micromachining

- Structuring of silicon in three dimensions using anisotropic etching
- High aspect ratio is possible.
- Crystal orientation decides the structure geometry



縱橫比＝H/W

圖 3.6　縱橫比的意義

Bulk Micromachining

- 蝕刻幾何形狀將沿著(111)晶面被切割
- 常用於橋、樑、薄膜等特徵的構造

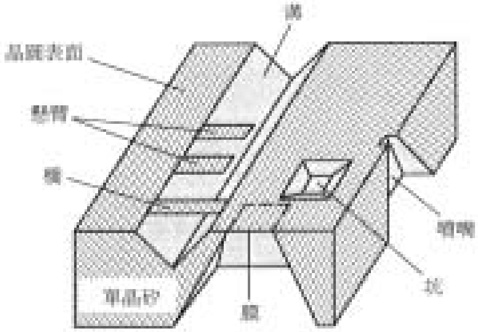


圖 4.14　各種立體微機械加工構造，根據 [Howe 90]。

Basic Structures in Silicon

- Anisotropic Etching of Silicon

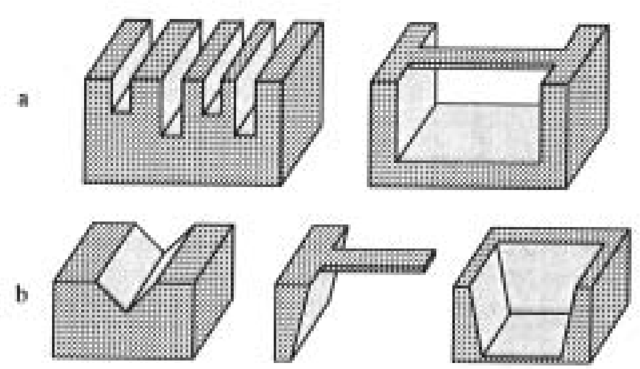
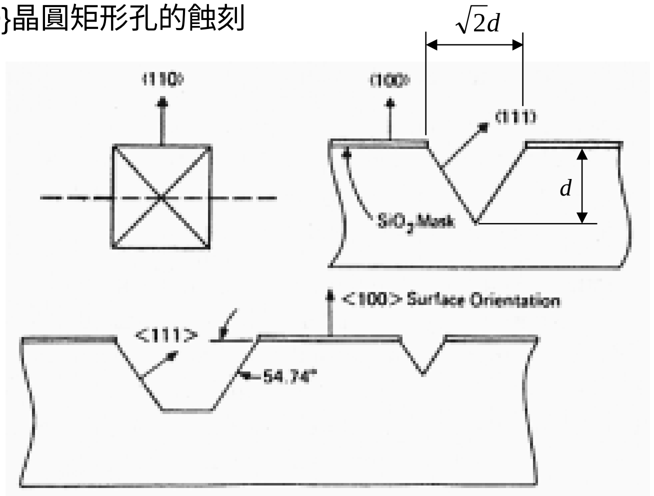


圖 4.9 能夠在 a (110) 矽；b) (100) 矽上製成之基本構造。

{100}晶圓的蝕刻角度

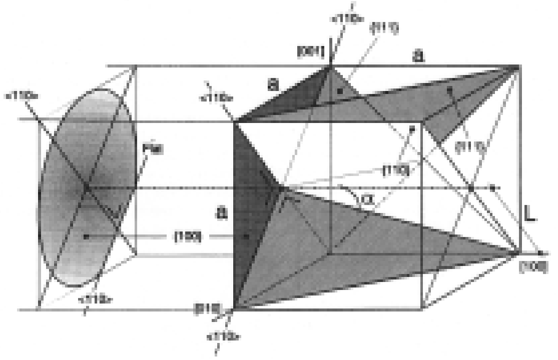
- {100}晶圓矩形孔的蝕刻



晶圓方向

- {100}晶圓的蝕刻夾角
  - {111}與{110}方向的夾角 $\alpha = \tan^{-1}((\sqrt{2}/2)/1) = 35.26°$
  - 亦可利用<111>與<110>向量的餘弦定理求出兩向量的夾角

$$1\cdot1+1\cdot1+1\cdot0=\sqrt{1+1+1}\sqrt{1+1+0}\cos\alpha$$



{100}晶圓的蝕刻夾角

- <111>與<100>向量的餘弦定理

$$1\cdot1+1\cdot0+1\cdot0=\sqrt{1+1+1}\sqrt{1+0+0}\cos\theta,\ \theta=54.74$$

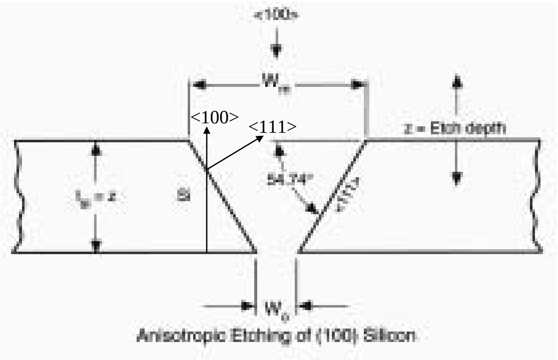
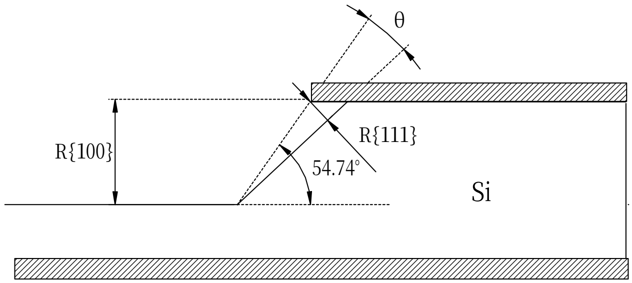


Figure 4.8 Relation of bottom cavity plane width with mask opening width.

Undercut of {100} Wafer

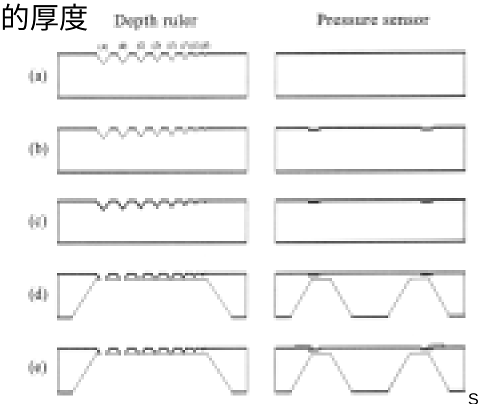
- Undercut due to finite selectivity between the etch rates of {111} and {100}.

$$\tan\theta = \sqrt{1/3} \times R\{111\} / R\{100\}$$



{100} V-Groove Depth Ruler

- 利用{100}晶圓V槽寬深比為$\sqrt{2}:1$ 的特性，由被蝕穿的孔判斷剩餘薄膜的厚度



Source: 認識微機電—楊龍杰

Anisotropic Etching in {110} Wafer

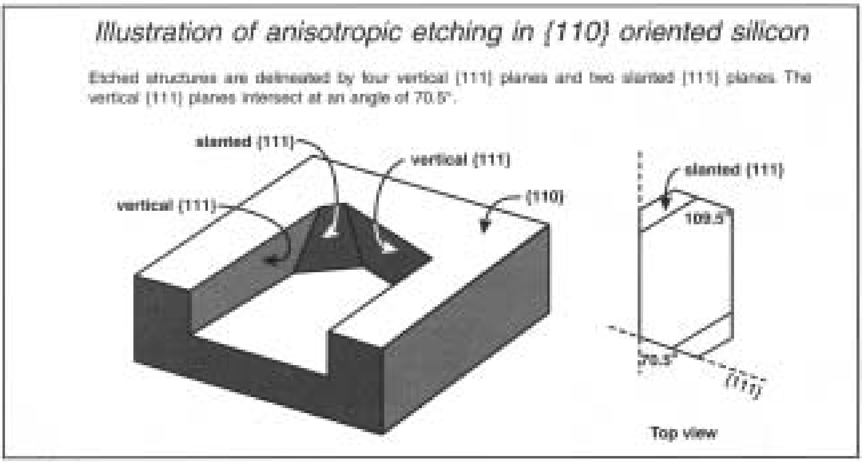


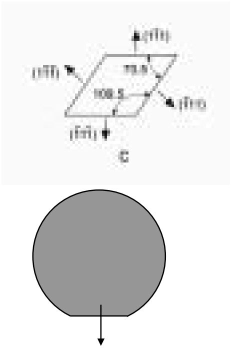
Illustration of anisotropic etching in {110} oriented silicon

Etched structures are delineated by four vertical {111} planes and two slanted {111} planes. The vertical {111} planes intersect at an angle of 70.5°.

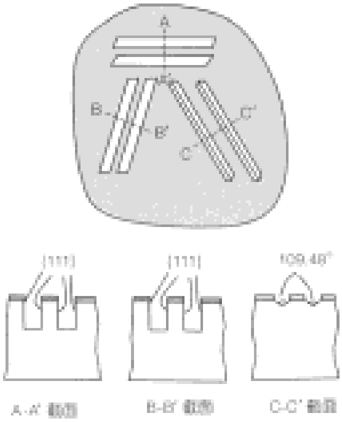
Inset 4.4

Anisotropic Etching in {110} Wafer

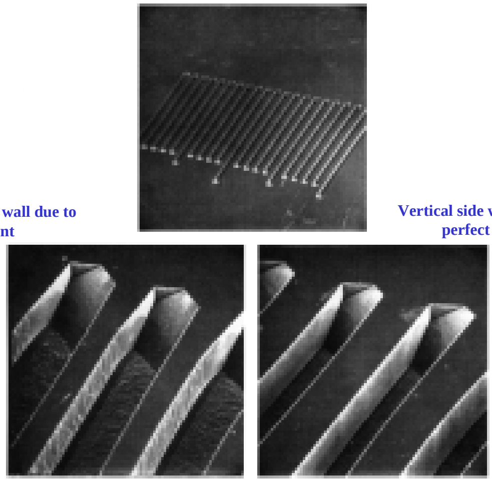
- {110}晶圓上不同角度矩形槽與蝕刻斷面的關係



<111>



Long Narrow Grooves in a <110> Wafer



Rough side wall due to misalignment

Vertical side wall due to perfect alignment

Figure 4.33 Long, narrow grooves in a <110> wafer. These U-grooves are used as test patterns. Test pattern of U-grooves in a <110> wafer help in the alignment of the mask; final alignment is done with the groove that exhibits the most perfect long perpendicular walls.

Selection of Silicon Wafer

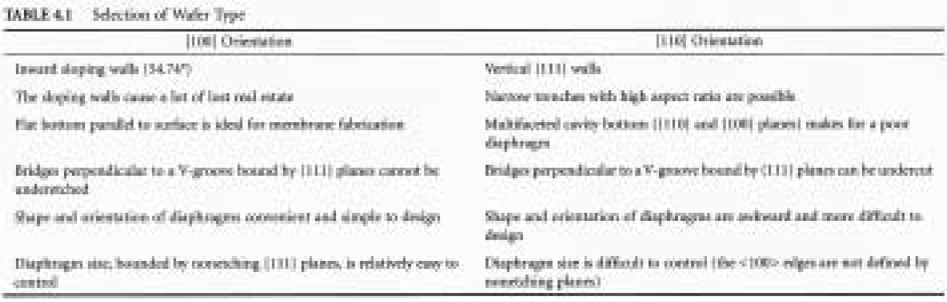
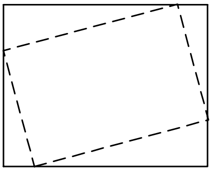


TABLE 4.1 Selection of Wafer Type

[100] Orientation	[110] Orientation
Inward sloping walls (54.74°)	Vertical [111] walls
The sloping walls cause a lot of lost real estate	Narrow trenches with high aspect ratio are possible
Flat bottom parallel to surface is ideal for membrane fabrication	Multifaceted cavity bottom ([110] and [100] planes) makes for a poor diaphragm
Bridges perpendicular to a V-groove bound by [111] planes cannot be underetched	Bridges perpendicular to a V-groove bound by [111] planes can be undercut
Shape and orientation of diaphragms convenient and simple to design	Shape and orientation of diaphragms are awkward and more difficult to design
Diaphragm size, bounded by nonetching [111] planes, is relatively easy to control	Diaphragm size is difficult to control (the <100> edges are not defined by nonetching planes)

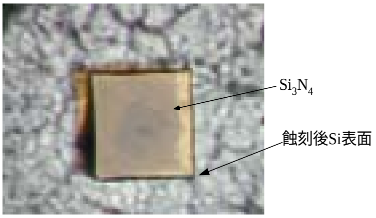
矽結構立體微細加工

- 矽微結構蝕刻缺陷
  - 底部蝕刻（underetch）
  - 底切（undercut）



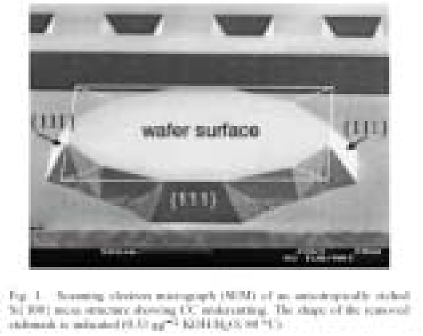
- - - -對位不準

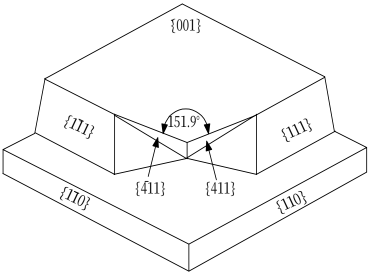
———實際蝕刻



矽結構凸角底切的現象

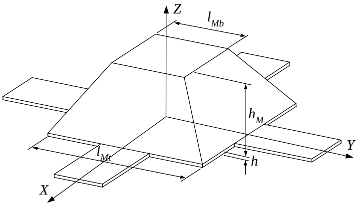
- 裸露的矽凸角特徵，在KOH蝕刻時產生底切的現象

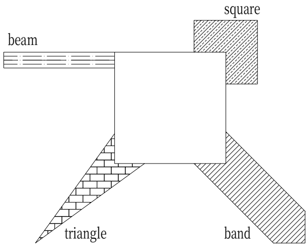


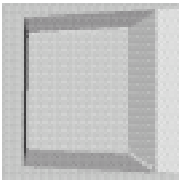


化學濕蝕刻的凸角補償

- 角落補償圖形設計原理
    - <100>延伸法
    - <110>延伸法
- 光罩補償蝕刻模擬

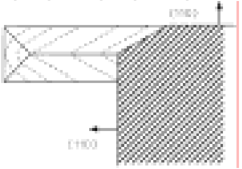


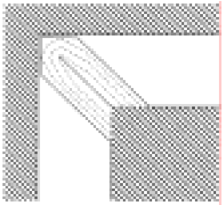



(band)

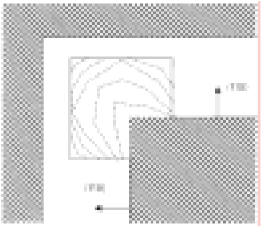
基本的光罩補償圖形

- {100}晶圓以KOH蝕刻的補償：
  蝕刻速率(110)>(100)>(111)



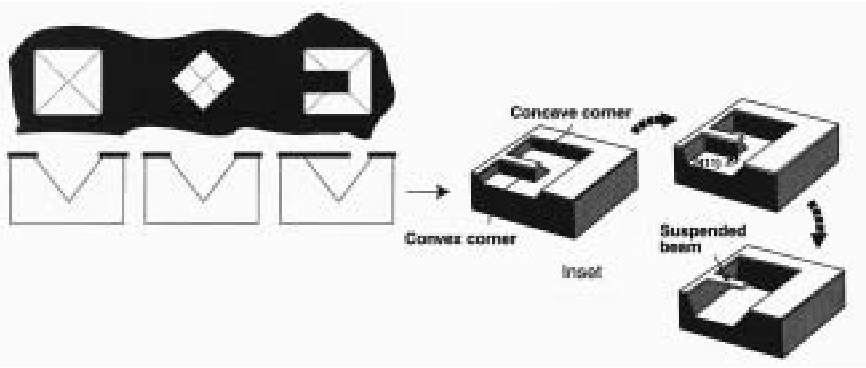


- {100}晶圓以EDP蝕刻的補償：
  蝕刻速率(100)>(110)>(111)



以濕蝕刻製作懸樑

- 利用凸角底切的特性掏空懸梁的底部



P+ Etch-Stop

- Doping the silicon substrate with germanium, phosphorus or boron atoms
- P^+ (Boron) concentration of about 10^{20} cm^{-3} or higher will drastically reduce etching rate
- Doping
  - Diffusion method
    - Difficult to get a uniform membrane thickness
  - Ion implantation
    - Good concentration and depth control but slow
    - 2 μm with a concentration of 10^{20} cm^{-3}, a 150 μA implanter needs up to an hour per wafer

Membrane using P+ Etch-Stop

- Boron doping
- Silicon layer by epitaxy
- Both sides oxidized
- Lithography of the silicon dioxide
- Anisotropic etching

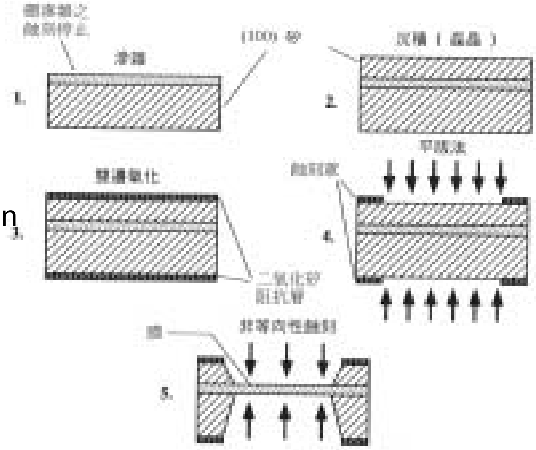


圖 4.15 使用 p^+ 蝕刻停止技術之膜的生產

Electrochemical Etch-Stop Technique

- Etching process is interrupted when an electric voltage is applied to an np or pn silicon substrate

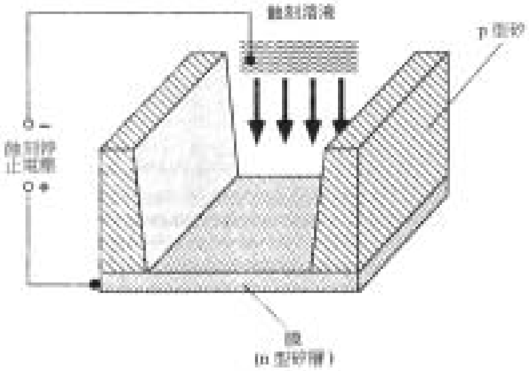


圖 4.16 由電化學的蝕刻停止法生成膜。

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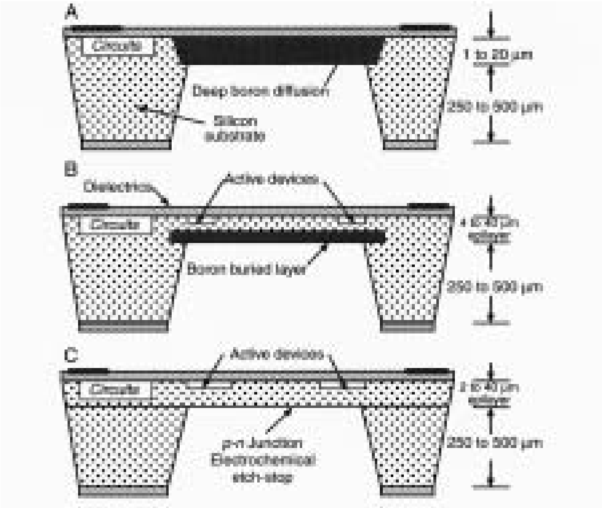
以蝕刻停止層製作薄膜結構



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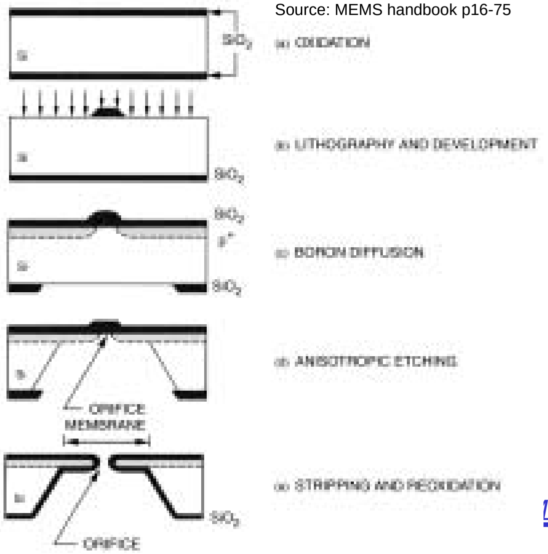
以蝕刻停止層製作薄膜噴嘴

Source: MEMS handbook p16-75



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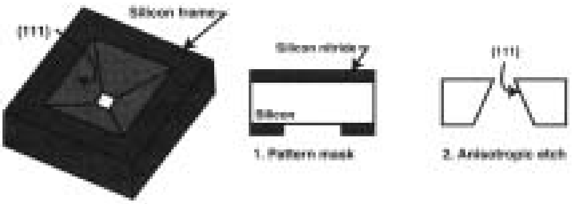
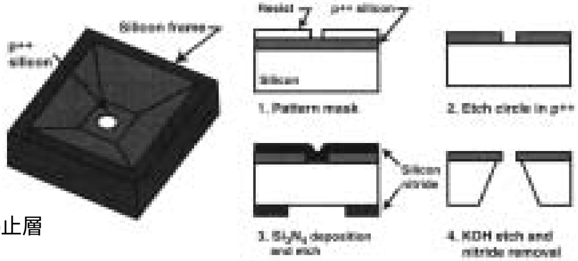
製作Membrane Nozzle的方式的比較



氮化矽方式

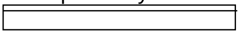


以硼植蝕刻停止層

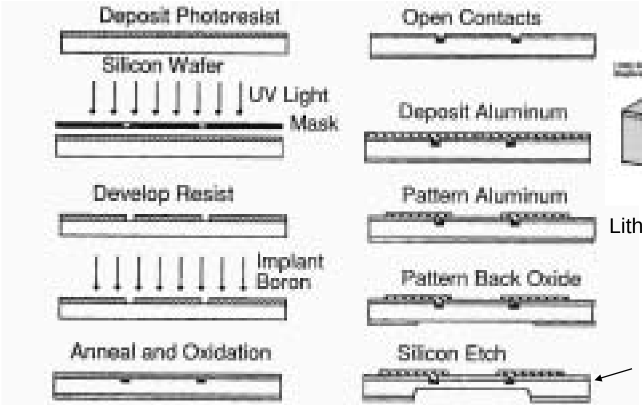
Piezoresistive Pressure Sensor

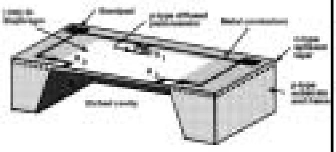
- Process of piezoresistive sensor using bulk micromachining

Eptixial layer n



Source: Fundamentals of Microfabrication, Madou, Fig 4.1





Lithography+RIE

Electrochemical etch stop

Surface Micromachining

- Planar structuring of the surface of a substrate
- Use thin layer techniques and selective etching
- Make complicated planar structures with a maximum thickness of a few micrometers

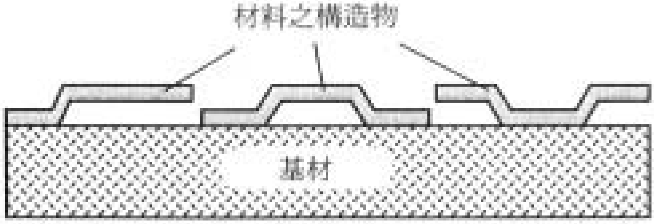


圖 4.17 典型的表面微機械加工構造

表面微細加工的基本步驟

- 沈積二氧化矽
- 以微影蝕刻在犧牲層（二氧化矽）上製作圖形
- 沈積複晶矽作為結構層
- 以微影製程與蝕刻製作複晶矽結構之幾何外型
- 以蝕刻法將犧牲層移去

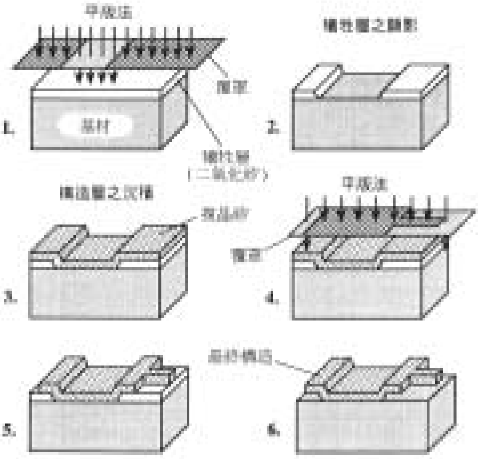


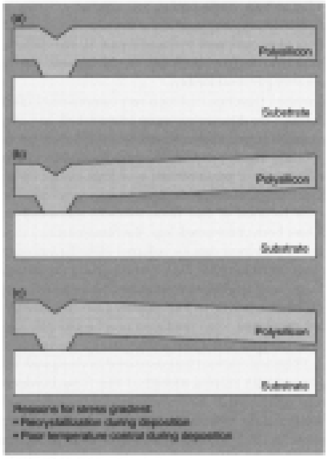
圖 4.18 表面微機械加工法製程之步驟，根據 [Sze 92]。

結構層與犧牲層的材料

- 多晶矽結構層
  - 犧牲層採低溫氧化矽（Low-Temperature Oxide, LTO）或磷矽酸玻璃(Phosphorous Silicate Glass, PSG)
  - 犧牲層蝕刻液為BOE(Buffer-Oxide-Etch; $HF:NH_4F=1:6$)
- 絕緣材料（氧化矽、氮化矽）為結構層
  - 犧牲層採金屬（鋁）
  - 犧牲層蝕刻液為非HF系之酸液
- 金屬為結構層
  - 以絕緣材料為犧牲層
  - 以化學電漿乾蝕刻（非氯系，如SF6）去除矽基絕緣犧牲層

殘留應力對薄膜件的影響

- 薄膜殘留應力將限制構造的側面尺寸
- 鍍膜製程的溫昇造成不同材質間的殘留熱應力
- 多晶矽（壓應力）與氮化矽（張應力）薄膜也會有殘留內應力
  - 多晶矽可藉調整LPCVD的溫度與降低壓力來減少內部應力
  - 氮化矽可以富矽(silicon rich)製程減低內應力，但在LPCVD爐管壁將殘留多晶矽，增加管壁清洗頻率



Stiction Phenomenon

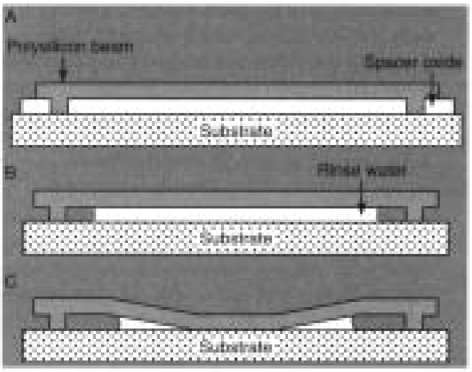


Figure 5.17 Stiction phenomenon in surface micromachining and the effect of surface tension on micromechanical structures. (A) Unreleased beam. (B) Released beam before drying. (C) Released beam pulled to the substrate by capillary forces as the wafer dries.

沾黏問題的處理

- 沾黏的原因
  - 液體表面張力將結構層下拉
  - 薄膜接觸基材時的凡得瓦爾力、氫鍵或其他鍵合力
- 解決沾黏的方式
  - 以相變化方式，先加壓降溫固化液體，再降壓使固體直接昇華
  - 浸泡如甲醇(methanol)或異丙醇(Iso-Propane Alcohol, IPA)有機溶濟取代純水再蒸乾，並配合事先製作的微小突起減少沾黏
  - 以電漿乾蝕刻方式除去犧牲層

Comb-like Free-standing Microstructure

- 以表面微細加工所製作的零件(From Polysilicon)
  - Beam: 0.8 μm wide and 2 μm high

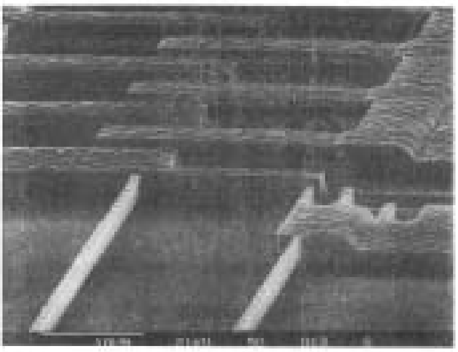


圖 4.19 表面微機械加工法之實施例，感謝 University of Neuchâtel (Institute of Microtechnology)

Microgripper

- Microgripper made from polysilicon using surface micromachining
- Moved by electrostatic force from comb-like actuators

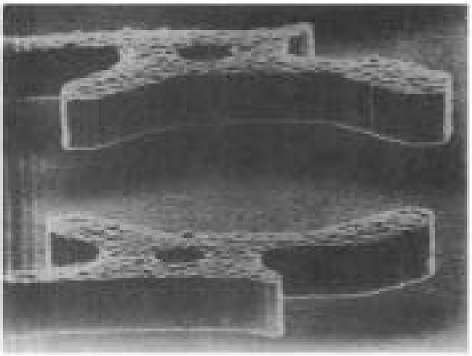


圖 4.20 以表面微機械加工法所製之微爪，感謝 the Berkeley Sensor and Actuator Center, University of California, Berkeley。

Electrostatic Micromotor

- Motor diameter: 100 μm
- Distance between rotor and stator: 1-2 μm.
- 15,000 rpm at 35V

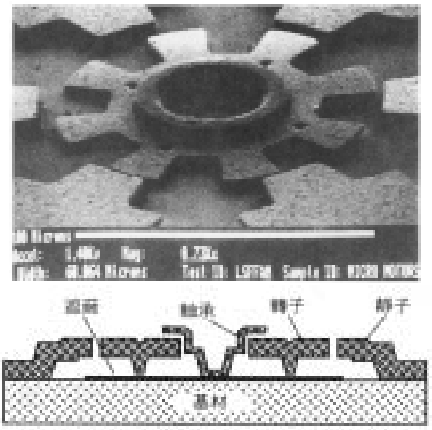
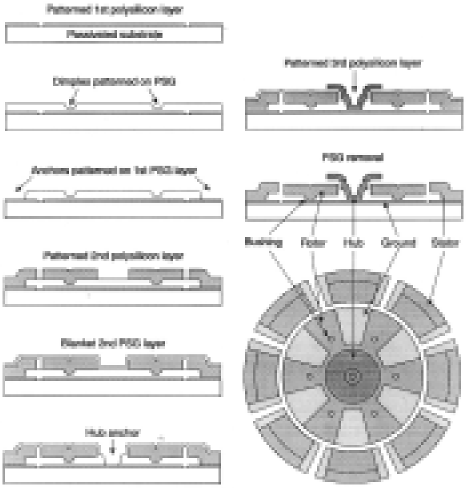


圖 4.21 以表面微機械加工法技術所製之靜電微馬達之剖面。根據 [MIT 92]。

Fabrication Procedure of MIT Micromotor



Source: Semiconductor sensors p69

- Patterned 1st polysilicon layer
- Dimples patterned on PSG
- Anchors patterned on 1st PSG
- Patterned 2nd polysilicon layer
- Blanket 2nd PSG layer
- Hub anchor
- Patterned 3rd polysilicon layer
- PSG removal

Optical Microshutter

- Drive by comb actuator
- Made from 2 μm polysilicon
- 光柵：100X30 μm
- Max. move: 8.3 μm

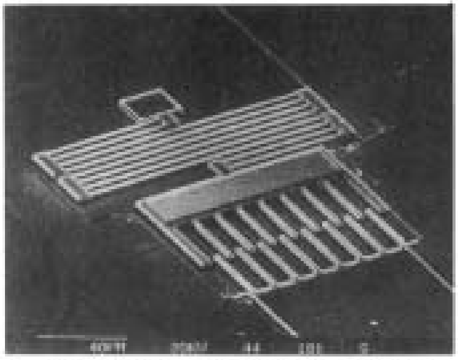


圖 4.22　由表面微機械加工技術所製之微柵。感謝 the University of Neuchâtel (Institute of Microtechnology)。

Optical Fiber Aligner

- Grooves made from anisotropic bulk micromachining on a single crystal silicon wafer
- Use in the light coupler

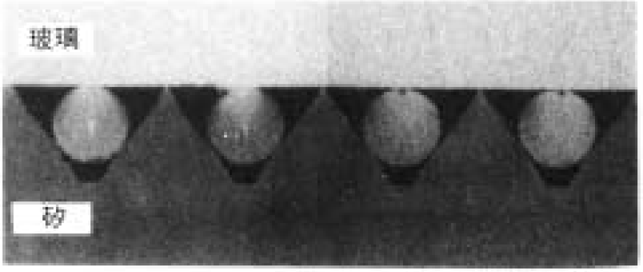
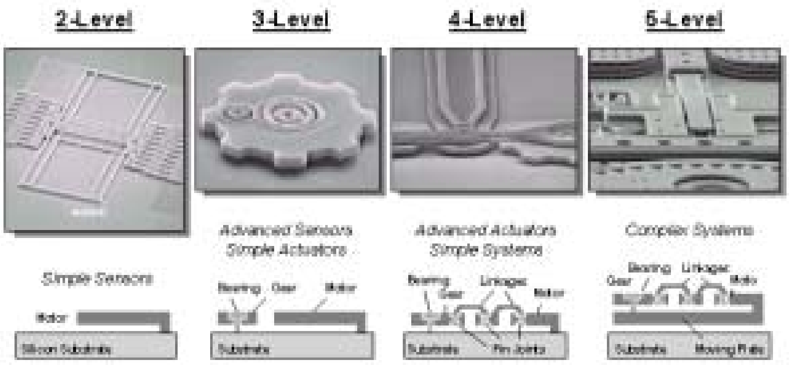


圖 4.23　由立體微機械加工法所製之光纖對準裝置。感謝 the Industrial Microelectronics Center, Kista。

Micro-Mechanical Devices

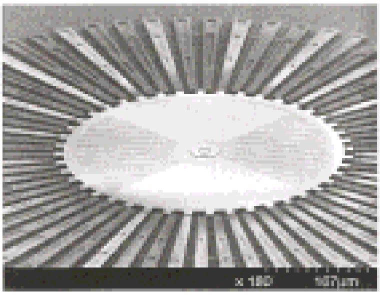
- 可重複以上步驟以獲得更複雜的立體微結構（可達20微米厚），但每層之間需鍍上氮化矽作為保護層

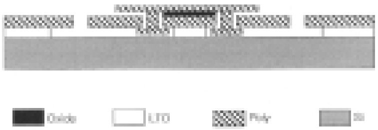
After Sandia National Laboratories, http://www.mdl.sandia.gov/micromachine



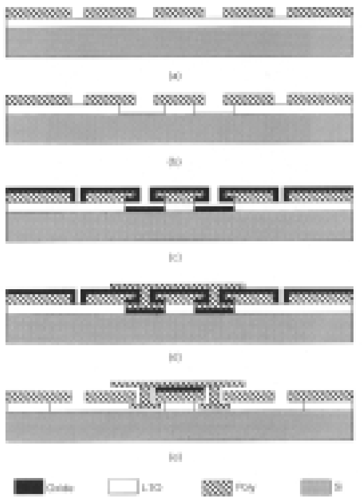
Micromotor using Rapid Prototyping

- Three deposition and three lithography





Micromotors by Surface Micromachining



- Deposit 2.4 μm LTO on Si substrate
- Deposit 2 μm doped polysilicon on LTO
- Photolithography and RIE on polysilicon to define rotor, stator, and rotor/stator gaps (a)
- Isotropic etching LTO to define flange(b)
- Oxidation to create bearing clearance oxide (c)
- Deposit 1~2 μm heavy-doped polysilicon film, and patterned by Photolithography and RIE (d)
- Release the rotor by etching the sacrificial oxide in HF (e)

Source: MEMS handbook p15-13

Bulk vs. Surface Micromachining

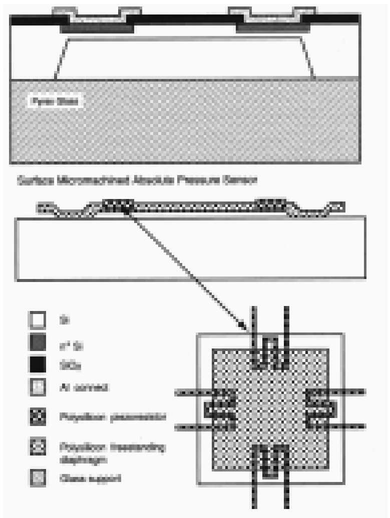


Figure 5.1 Comparison of bulk micromachined and surface micromachined absolute pressure sensors equipped with piezoresistive elements. (Top) Bulk micromachining in single-crystal Si. (Bottom) Surface micromachining with poly-Si.

Source: MEMS handbook p16-95

雷射加工

- 基本架構：二平行鏡面間形成一光學諧振腔(optical oscillator)，光反覆震盪二鏡面間的激發介質，藉激發射將此光震盪現象放大
- 依激發介質可分為固態雷射、液態雷射、氣態雷射與半導體雷射等，其中適合加工的雷射有
  - CO_2雷射（波長10.6微米）
  - Nd:YAG（釹釔鋁石榴石）雷射（波長1.06微米）
  - Nd glass（釹玻璃）雷射
  - Excimer Laser（準分子雷射）
    - 依不同激發氣體有ArF (193nm), KrF (248nm), XeCl (308nm), XeF (351nm)

雷射種類

相	種類	活性物質	振盪波長	形態	特徵	應用例
氣體	He-Ne雷射	Ne	632.8nm	連續	功率雖小但可作同調性佳的穩定輸出、操縱簡單	測量、空中傳播、顯示、光記憶體、印表機
	氬氣雷射	Ar	488nm 514.5nm	連續	功率大且可作同調性佳的定輸出	量測、水中通信、凝結器、IC光罩加工、顯示器
	二氧化碳氣體雷射	CO2	10.6µm	連續	高輸出、高效率 紅外線	加工、雷射手術刀、量測、雷射雷達
	氮氣雷射	N2	337.1nm	脈衝	短脈衝 近紫外線	分光研究、色素雷射用激發光源
	準分子雷射	ArF、KrF、XeCl、XeF	193、248、308、351nm	脈衝	高輸出 紫外線	光化學反應加工、色素雷射用淚發光源、脈射雷達
	金屬蒸汽雷射	Cu、Au	511、578 628nm	脈衝	高速度往復 平均輸出大	色素雷射用激發源、高速度攝影機用光源

雷射種類

相	種類	活性物質	振盪波長	形態	特徵	應用例
液體	色素雷射	Rhodamine6G coumarin 其它	0.32~1.2nm	脈衝 連續	振盪波長寬 波長可變	研究用光源、同位體分離、雷射雷達
固體	紅寶石雷射	Cr	694.3nm	脈衝	高能量脈衝 高功率輸出	量測、雷射雷達
	YAG雷射	Nd	1.06µm	脈衝 連續	高能量脈衝、高輸出、高速往復	加工、雷射手術刀、雷射雷達
	玻璃雷射	Nd0	1.05µm	脈衝	超高能量單一脈衝	雷射核融合
	半導體雷射	GaAlAs/GaAs InGaAsP/InP (PbSn)SnTe	0.84nm 1.2~1.6µm 2~20µm	脈衝 連續	袖珍、可直接調整脈衝	光通信、光計算機、光記憶體、雷射光碟

雷射加工

- ■ 傳統雷射加工
  - CO$_2$雷射與Nd:YAG雷射採熱加工，乃以雷射光束在工件照射處加熱，使之熔化或氣化。在加工金屬時會有熱影響區的問題
- ■ Excimer雷射加工
  - 高能量紫外光直接破壞照射處材料鍵結，為冷加工
  - 可加工金屬、高分子材料、陶瓷、介電材料
  - 包括剝蝕(ablation)與蝕刻(etching)兩種機制
    - 剝蝕：受高強度雷射脈衝照射後直接排出材料的加工機制
    - 蝕刻：配合氣體或液體與材料產生化學反應
  - 可應用於微光刻、微機械加工、表面處理/沈積

不同雷射加工的表面特徵

- CO$_2$雷射與Nd:YAG雷射採熱加工，在加工金屬時會有熱影響區的問題。
- Excimer雷射加工，直接破壞照射處材料鍵結，加工面平整

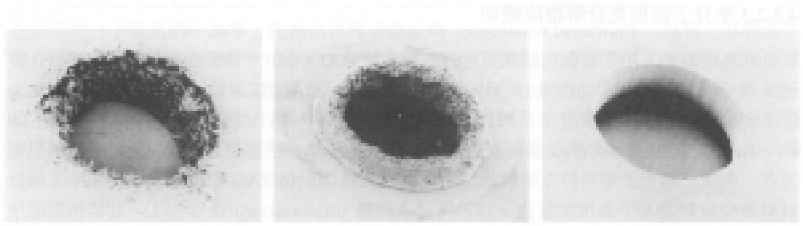


圖 4.52 比較聚亞醯胺以不同雷射加工的結果：(a) Nd:YAG 雷射；(b) CO$_2$ 雷射；(c) 準分子雷射。

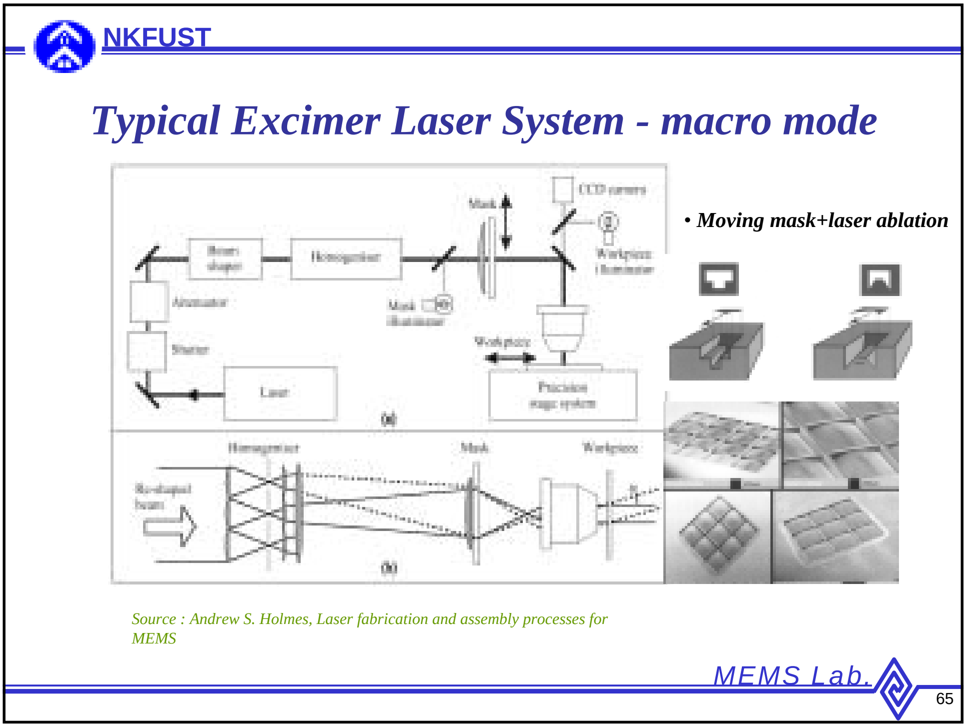
Why “Excimer” Laser?

- Short wavelength, high image resolution

min. laser beam size $d_{min} = f\lambda/\pi d_o$

- High power density
- Strong absorption by polymer leads to efficient laser-target coupling and small heat-affected zone, i.e.. precise dimension control !

Type	Wavelength	Pulse width/energy	Min. feature size	Structure height
Excimer (ArF, KrF)	193, 248 nm	20 ns/500 mJ	2 um	< 200 um
Nd:YAG	1.064 um	~ 10 ns/10mJ	50 um	< 200 um



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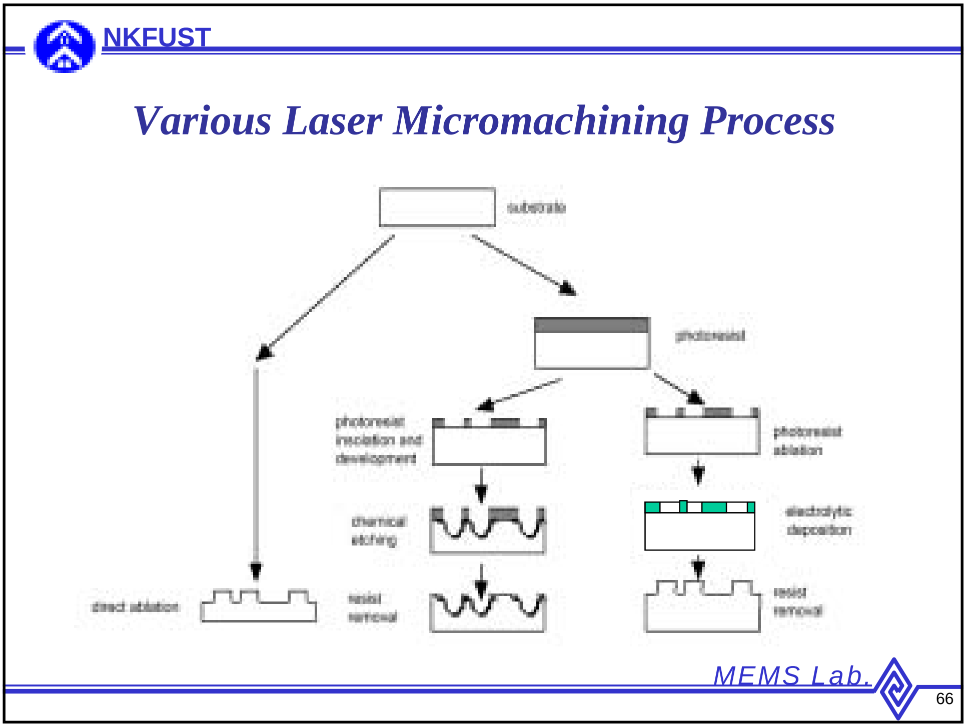
Typical Excimer Laser System - macro mode

- ***Moving mask+laser ablation***

Source : Andrew S. Holmes, Laser fabrication and assembly processes for MEMS

MEMS Lab.



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Various Laser Micromachining Process

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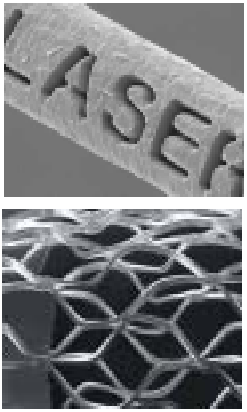
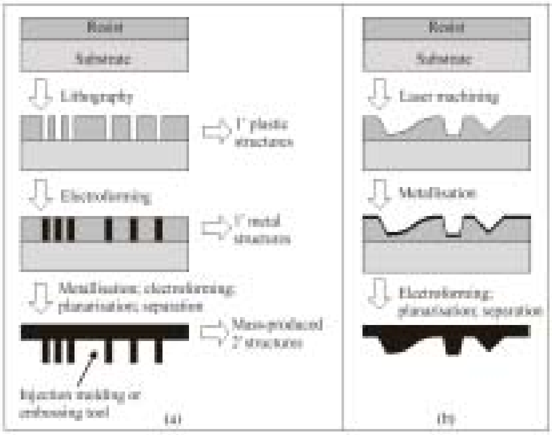
3D Laser Micromachining



Source : http://www.fzk.de/pmt/



Source : Andrew S. Holmes, Laser fabrication and assembly processes for MEMS