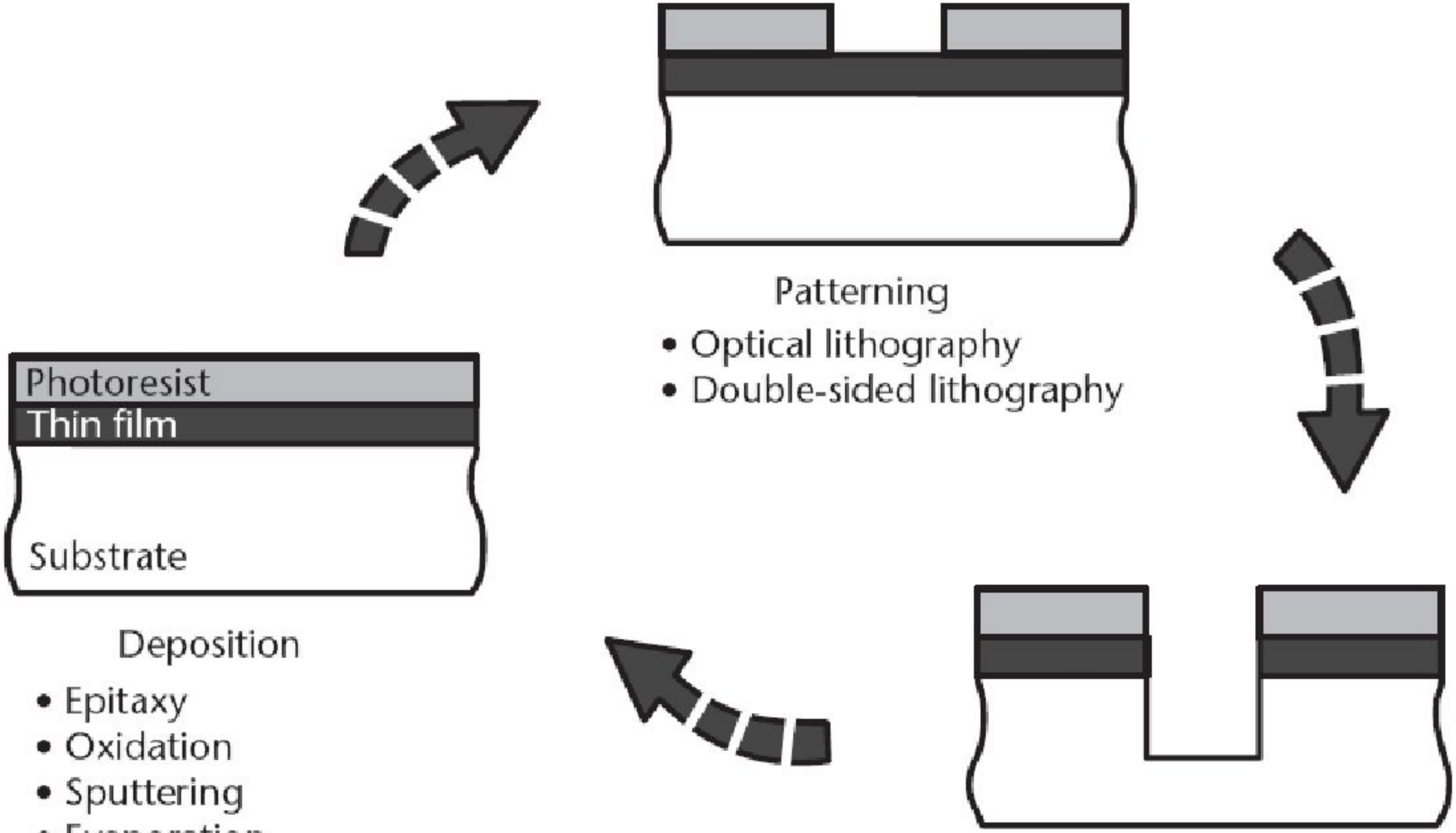
Наномеханика

Nanomechanics of materials and systems

Лекция 12
Материалы и технологии изготовления
нано- и микро-электромеханических систем
НЭМС/МЭМС
Materials and technologies of nano- and
micro-electro-mechanical systems
NEMS/MEMS

Базовый цикл создания НЭМС. Base cycle of NEMS formation.



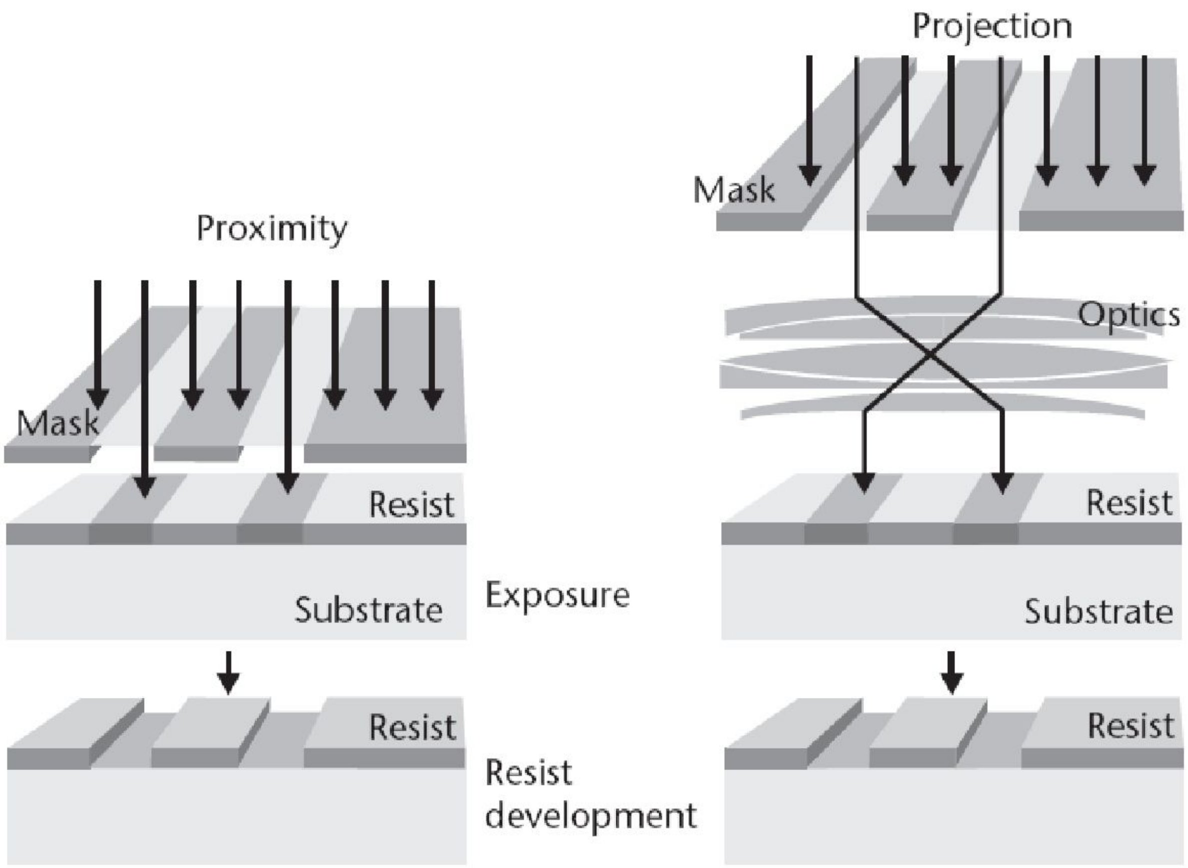
Patterning
- Optical lithography
- Double-sided lithography

Deposition
- Epitaxy
- Oxidation
- Sputtering
- Evaporation
- CVD/LPCVD/PECVD
- Spin-on method
- Sol-gel
- Anodic bonding
- Silicon fusion bonding

Etching
- Wet isotropic
- Wet anisotropic
- Plasma
- RIE
- DRIE

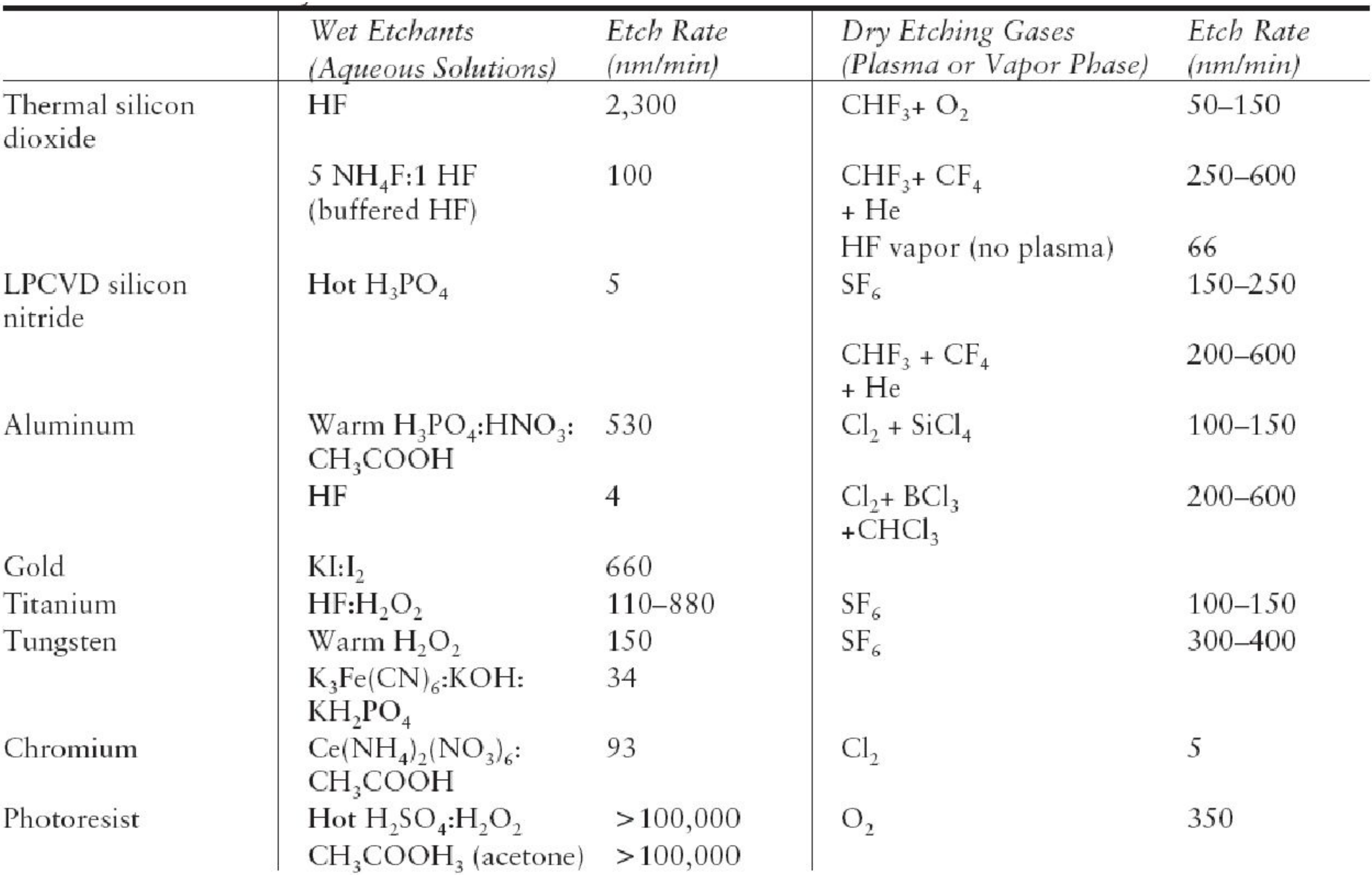
Литография Lithography

- Нанесение резиста
- Перенесение изображения маски на резист
- Селективное травление резиста и материала под ним



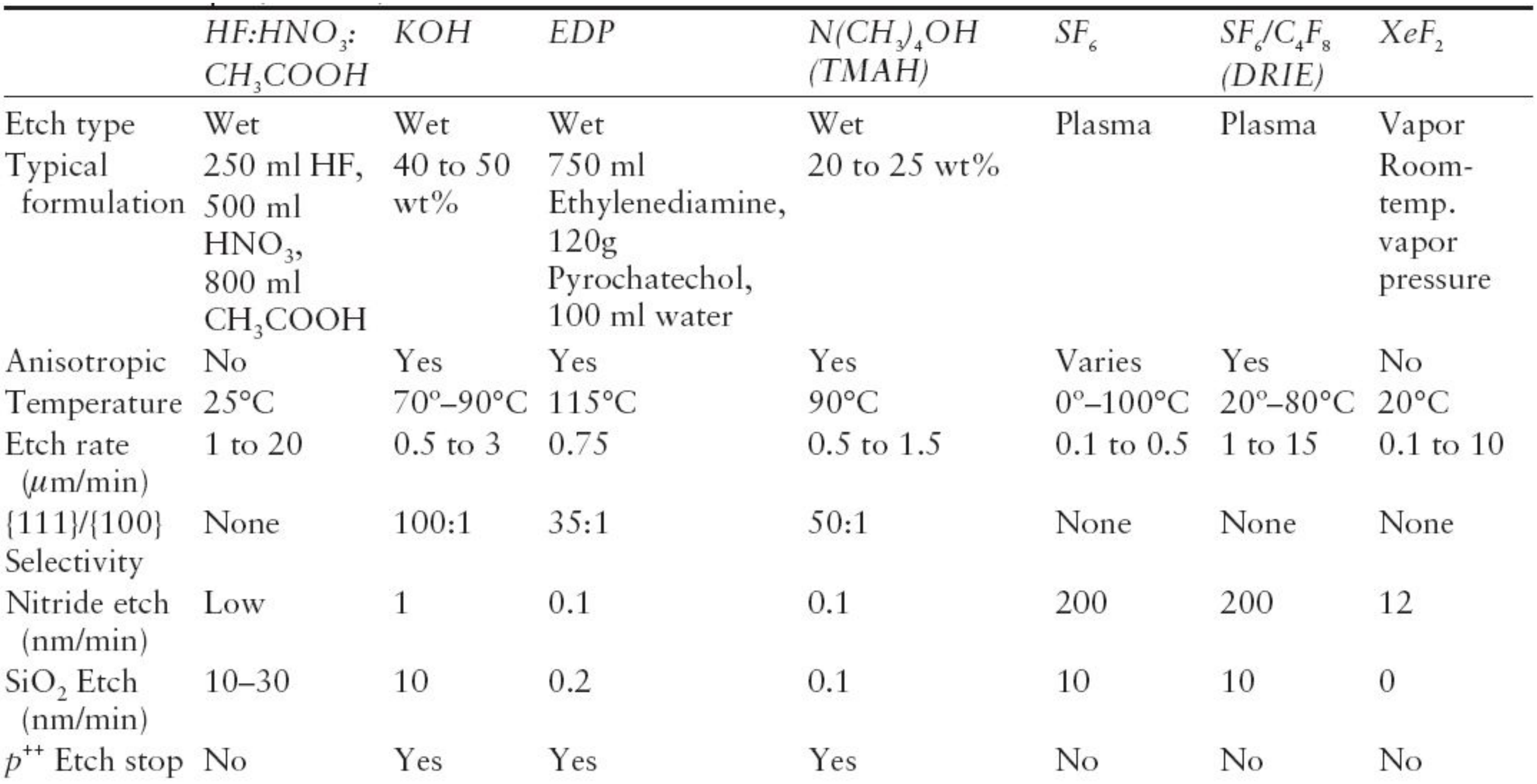
An illustration of proximity and projection lithography. In proximity mode, the mask is within 25 to 50 μm of the resist. Fresnel diffraction limits the resolution and minimum feature size to ~ 5 μm. In projection mode, complex optics image the mask onto the resist. The resolution is routinely better than one micrometer. Subsequent development delineates the features in the resist.

Травление Etching



	Wet Etchants (Aqueous Solutions)	*Etch Rate (nm/min)*	*Dry Etching Gases (Plasma or Vapor Phase)*	*Etch Rate (nm/min)*
Thermal silicon dioxide	HF	2,300	$CHF_3 + O_2$	50–150
	5 NH_4F:1 HF (buffered HF)	100	$CHF_3 + CF_4 + He$	250–600
			HF vapor (no plasma)	66
LPCVD silicon nitride	Hot H_3PO_4	5	SF_6	150–250
			$CHF_3 + CF_4 + He$	200–600
Aluminum	Warm $H_3PO_4:HNO_3:CH_3COOH$	530	$Cl_2 + SiCl_4$	100–150
	HF	4	$Cl_2 + BCl_3 + CHCl_3$	200–600
Gold	$KI:I_2$	660		
Titanium	$HF:H_2O_2$	110–880	SF_6	100–150
Tungsten	Warm H_2O_2	150	SF_6	300–400
	$K_3Fe(CN)_6:KOH:KH_2PO_4$	34		
Chromium	$Ce(NH_4)_2(NO_3)_6:CH_3COOH$	93	Cl_2	5
Photoresist	Hot $H_2SO_4:H_2O_2$	>100,000	O_2	350
	CH_3COOH_3 (acetone)	>100,000		

Травление кремния Etching of Si

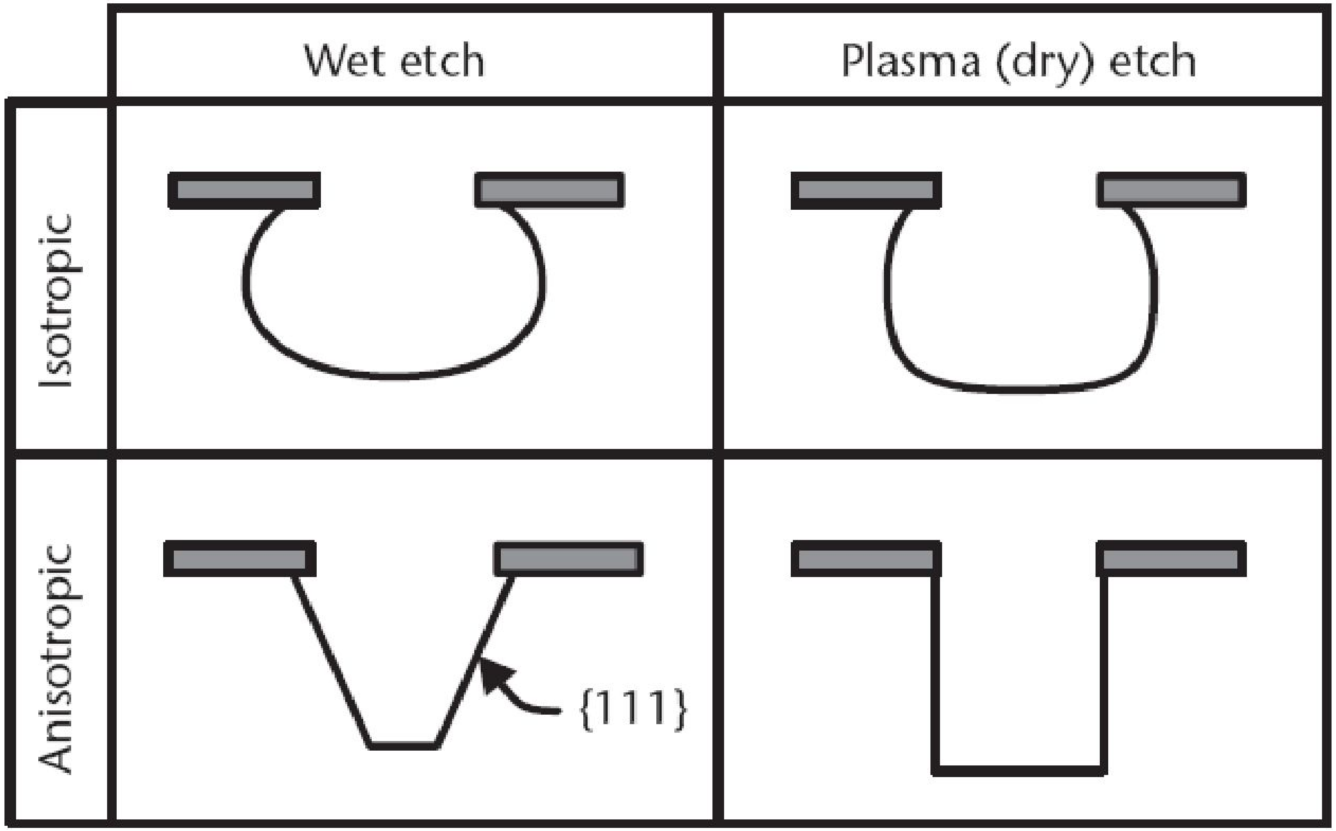


	$HF:HNO_3:CH_3COOH$	KOH	EDP	$N(CH_3)_4OH$ (TMAH)	SF_6	SF_6/C_4F_8 (DRIE)	XeF_2
Etch type	Wet	Wet	Wet	Wet	Plasma	Plasma	Vapor
Typical formulation	250 ml HF, 500 ml HNO_3, 800 ml CH_3COOH	40 to 50 wt%	750 ml Ethylenediamine, 120g Pyrochatechol, 100 ml water	20 to 25 wt%			Room-temp. vapor pressure
Anisotropic	No	Yes	Yes	Yes	Varies	Yes	No
Temperature	25°C	70°–90°C	115°C	90°C	0°–100°C	20°–80°C	20°C
Etch rate (μm/min)	1 to 20	0.5 to 3	0.75	0.5 to 1.5	0.1 to 0.5	1 to 15	0.1 to 10
{111}/{100} Selectivity	None	100:1	35:1	50:1	None	None	None
Nitride etch (nm/min)	Low	1	0.1	0.1	200	200	12
SiO_2 Etch (nm/min)	10–30	10	0.2	0.1	10	10	0
p^{++} Etch stop	No	Yes	Yes	Yes	No	No	No

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

$$\mathrm{Si(OH)}_2{}^{++} + 4e^- + 4\mathrm{H}_2\mathrm{O} \rightarrow \mathrm{Si(OH)}_6{}^{--} + 2\mathrm{H}_2 \,(reduction)$$

Профиль травления Etch profile



Schematic illustration of cross-sectional trench profiles resulting from four different types of etch methods.

Анизотропное травление Anisotropic etching

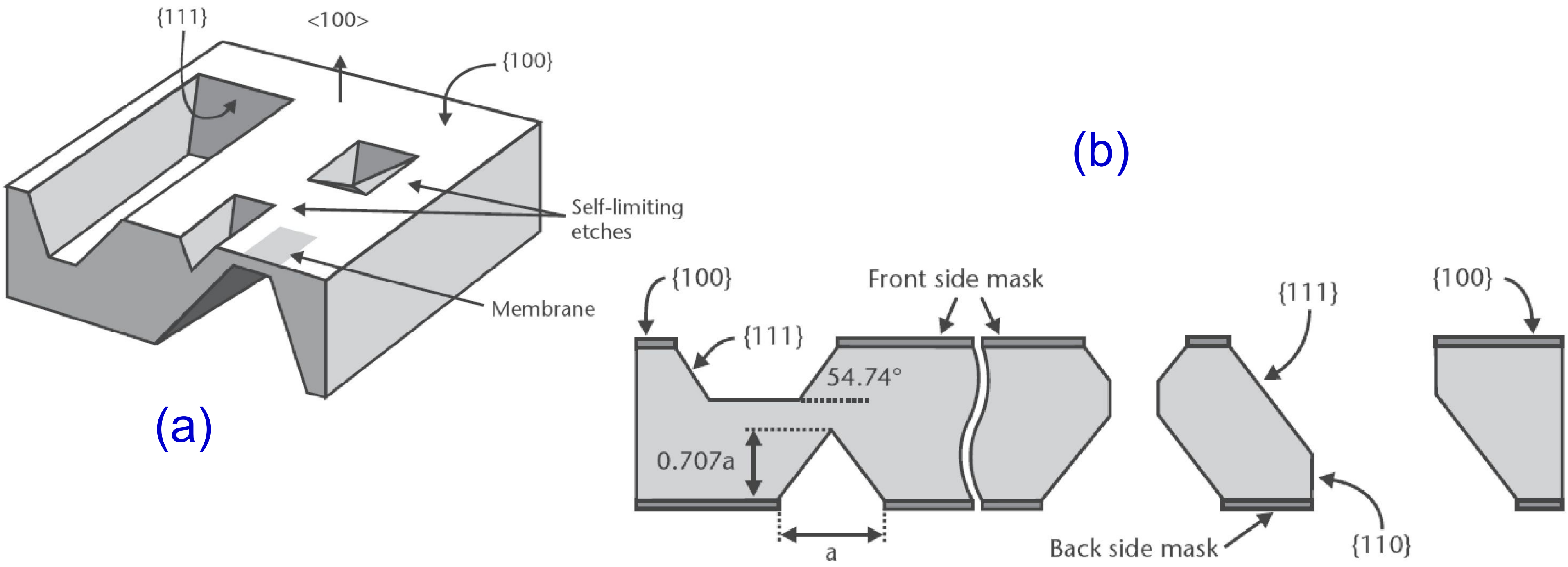


Illustration of the anisotropic etching of cavities in {100}-oriented silicon: (a) cavities, self-limiting pyramidal and V-shaped pits, and thin membranes; and (b) etching from both sides of the wafer can yield a multitude of different shapes including hourglass-shaped and oblique holes. When the vertically moving etch fronts from both sides meet, a sharp corner is formed. Lateral etching then occurs, with fast-etching planes such as {110} and {411} being revealed.

Анизотропное травление Anisotropic etching

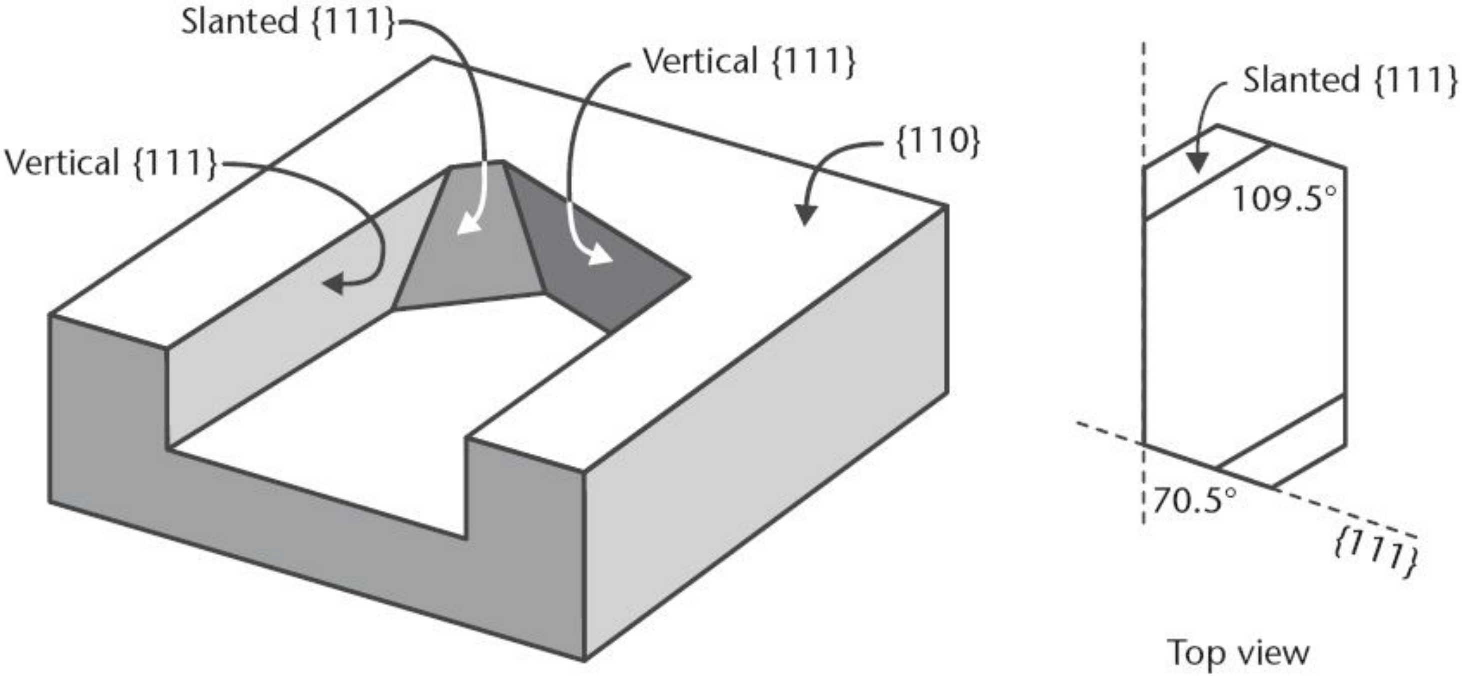


Illustration of the anisotropic etching in {110}-oriented silicon. Etched structures are delineated by four vertical {111} planes and two slanted {111} planes. The vertical {111} planes intersect at an angle of 70.5º.

Формирование подвешенных нано-балок
Suspended nano/micro beams

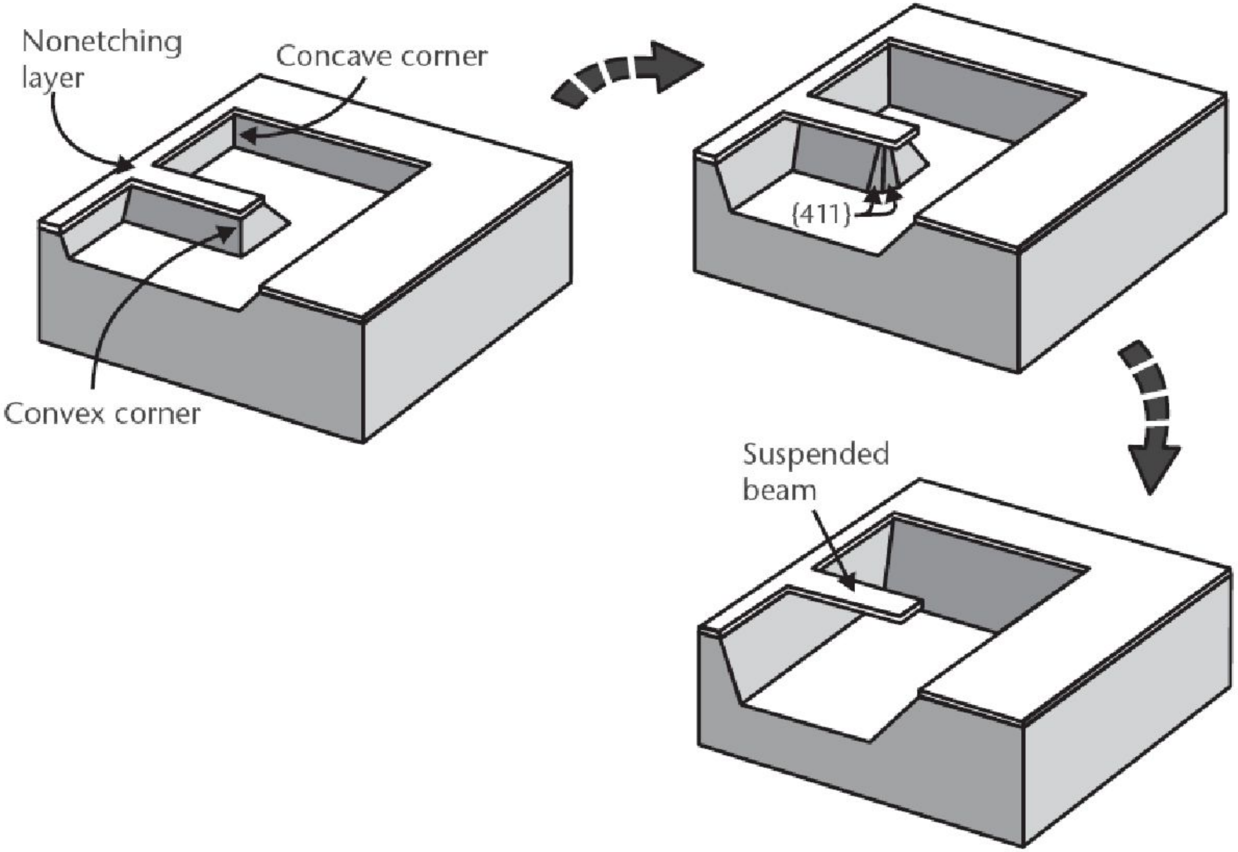
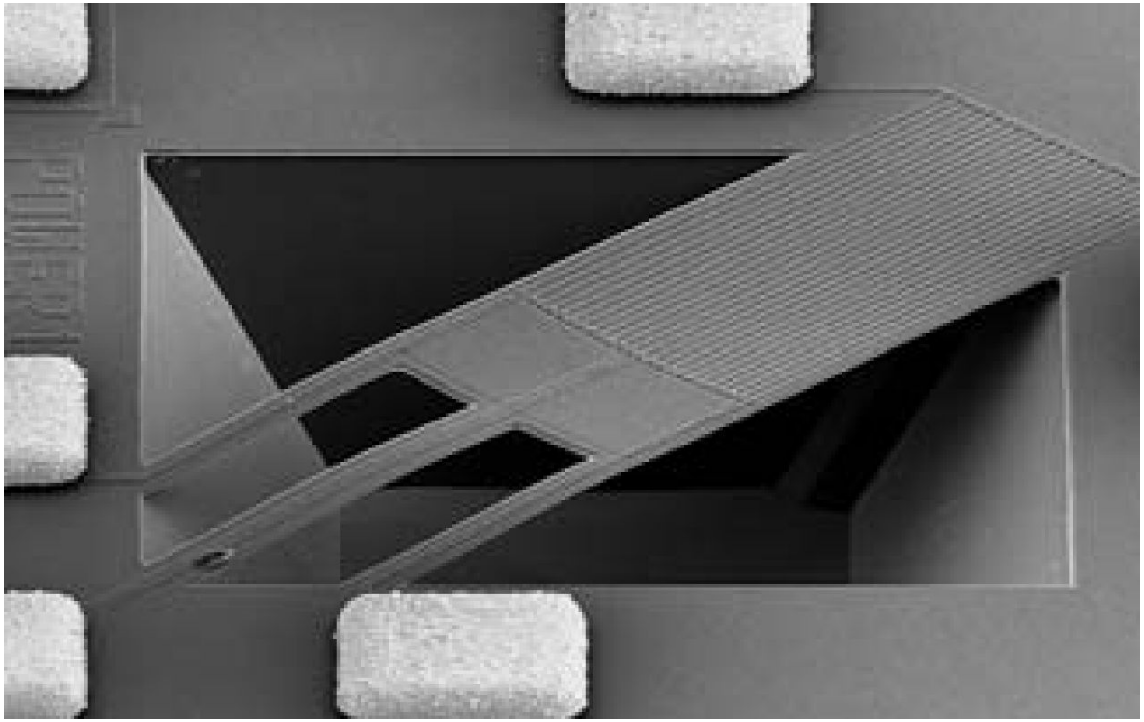


Illustration of the etching at convex corners and the formation of suspended beams of a material that is not etched (e.g., silicon nitride, *p*++ silicon). The {411} planes are frequently the fastest etching and appear at convex corners.

Мембрана над полостью Suspended membrane



Scanning-electron micrograph of a thermally isolated RMS converter consisting of thermopiles on a silicon dioxide membrane. The anisotropic etch undercuts the silicon dioxide mask to form a suspended membrane. (*Courtesy of:* D. Jaeggi, Swiss Federal Institute of Technology of Zurich, Switzerland.)

Электро-химическое травление Electro-chemical etching

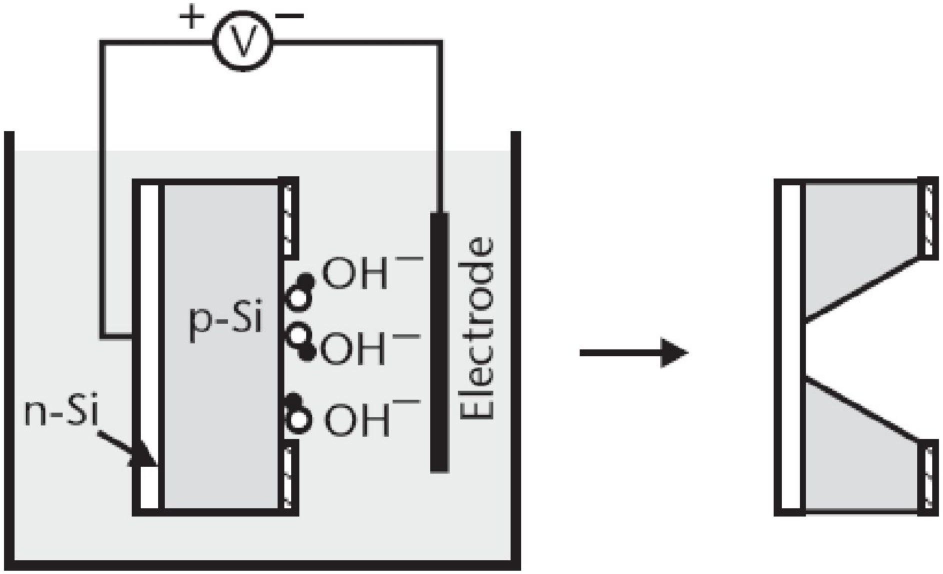
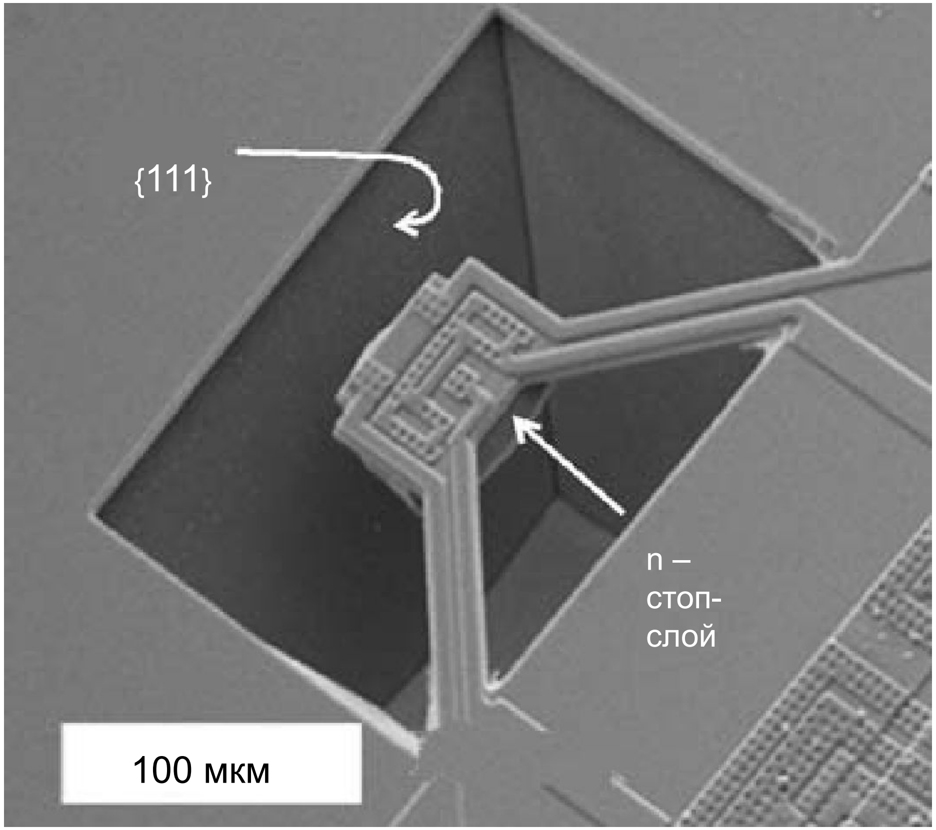


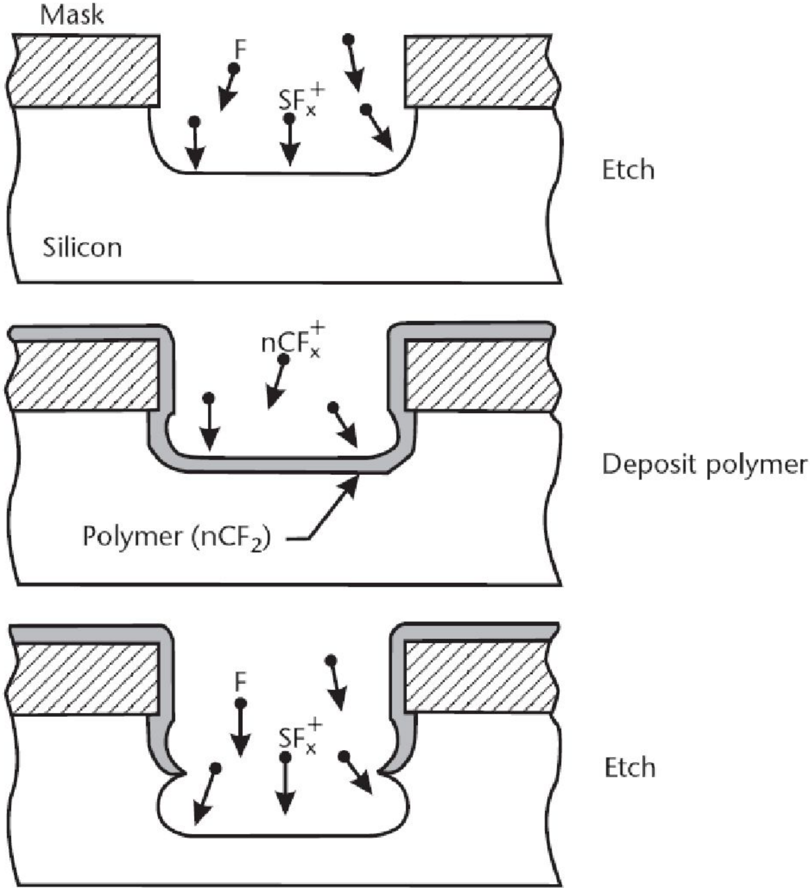
Illustration of electrochemical etching using *n*-type epitaxial silicon. The *n*-type silicon is biased above its passivation potential so it is not etched. The *p*-type layer is etched in the solution. The etch stops immediately after the *p*-type layer is completely removed.

Подвешенный островок кремния Suspended Si island



A fully suspended *n*-type crystalline silicon island electrochemically etched in TMAH after the completion of the CMOS processing. (*Courtesy of:* R. Reay, Linear Technology, Inc., of Milpitas, California, and E. Klaassen, Intel Corp. of Santa Clara, California.)

DRIE

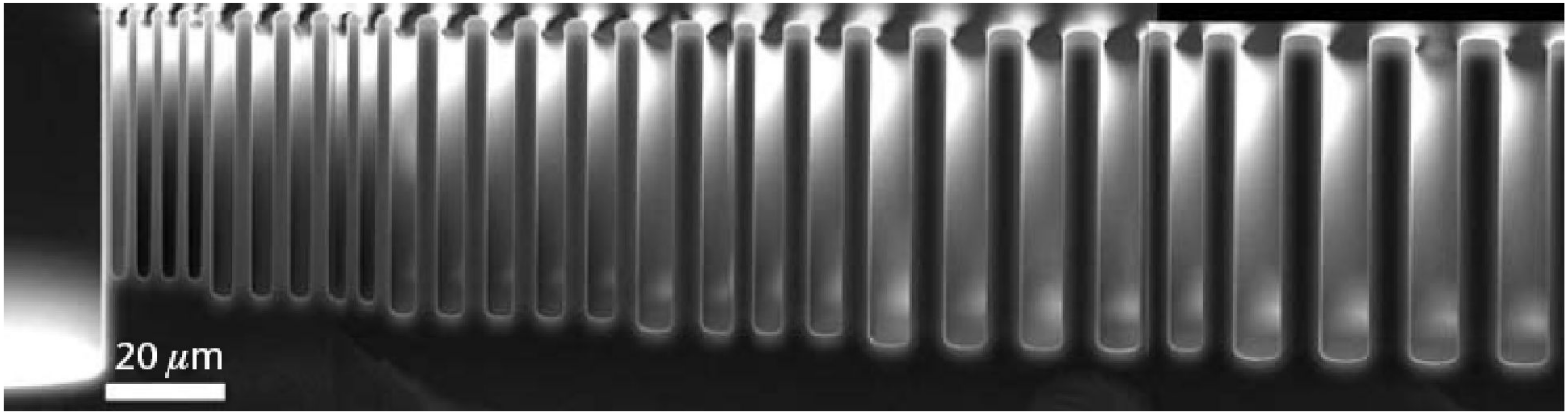


Характеристики процесса травления DRIE

Etch step	5–15s
SF_6 flow	80–150 sccm
Etch power to coil	600–2,500W
Etch power to platen	5–30W
Deposition step	5–12s
C_4F_8 flow	70–100 sccm
Deposition power to coil	600–1,500W
Pressure	0.5–4 Pa
Platen temperature	0°–20°C
Etch rate	1–15 μm/min
Sidewall angle	90° ± 2°
Selectivity to photoresist	≥ 40 to 1
Selectivity to SiO_2	≥ 100 to 1

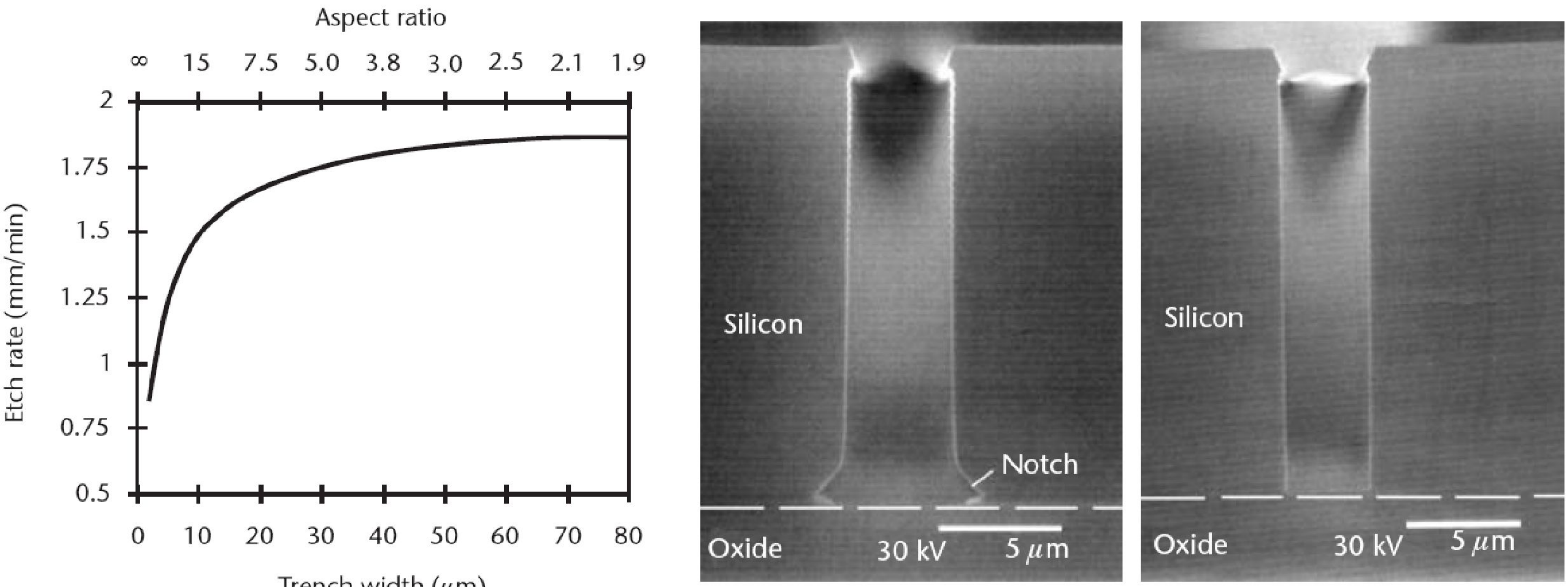
Profile of a DRIE trench using the Bosch process. The process cycles between an etch step using SF_6 gas and a polymer deposition step using C_4F_8. The polymer protects the sidewalls from etching by the reactive fluorine radicals. The scalloping effect of the etch is exaggerated.

Зависимость скорости травления от формы. Aspect-ratio-dependent etching in DRIE.



The etch rate decreases with increasing trench aspect ratio. (*Courtesy of:* GE NovaSensor of Fremont, California.)

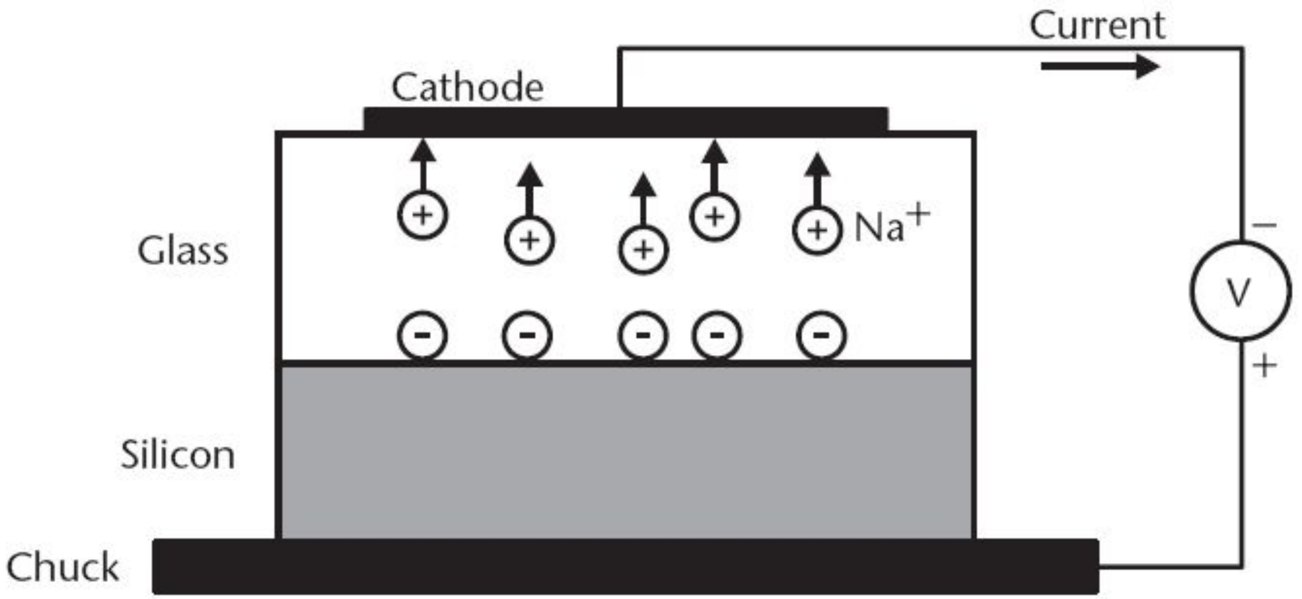
DRIE



(a) (b) (c)

(a) Etch-rate dependence on feature size and aspect ratio for a typical DRIE recipe at 600W. (b) Lateral etch observed at the interface between silicon and buried oxide layers, and (c) undercut eliminated with different recipe. (*Courtesy of:* Surface Technology Systems, Ltd., Newport, United Kingdom.)

Анодное сращивание. Anodic bonding



V = 0.5-1.5 kV

T = 200-500 °C

Illustration of anodic bonding between glass and silicon. Mobile sodium ions in the glass migrate to the cathode, leaving behind fixed negative charges. A large electric field at the silicon-glass interface holds the two substrates together and facilitates the chemical bonding of glass to silicon.

Прямое сращивание кремния и поликремния
Direct bonding of Si

Требования к исходным пластинам Si или поли-Si (Requirements):

Шероховатость не более Roughness < 0.5 nm

Отклонение от плоскости поверхности не более
deviation out of plane < 5 µm over 100 mm

Отсутствие химических загрязнений на поверхности
Chemically clean

Основные этапы процесса сращивания Steps:

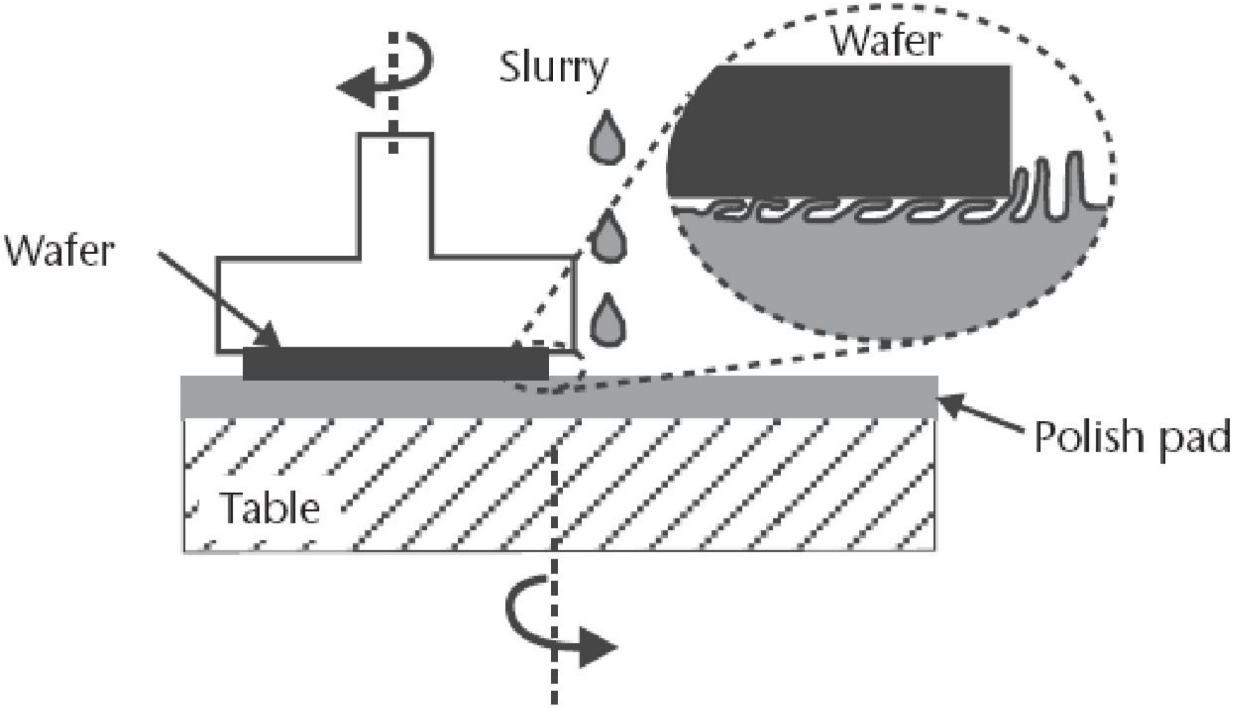
Химическая очистка поверхности и формирование на ней гидроксильных групп. Chemical cleaning, hydroxyl coverage.

Приведение сращиваемых поверхностей в контакт и соединение за счет сил Ван-дер-Вальса.
Contacting and Van-der-Waals bonding.

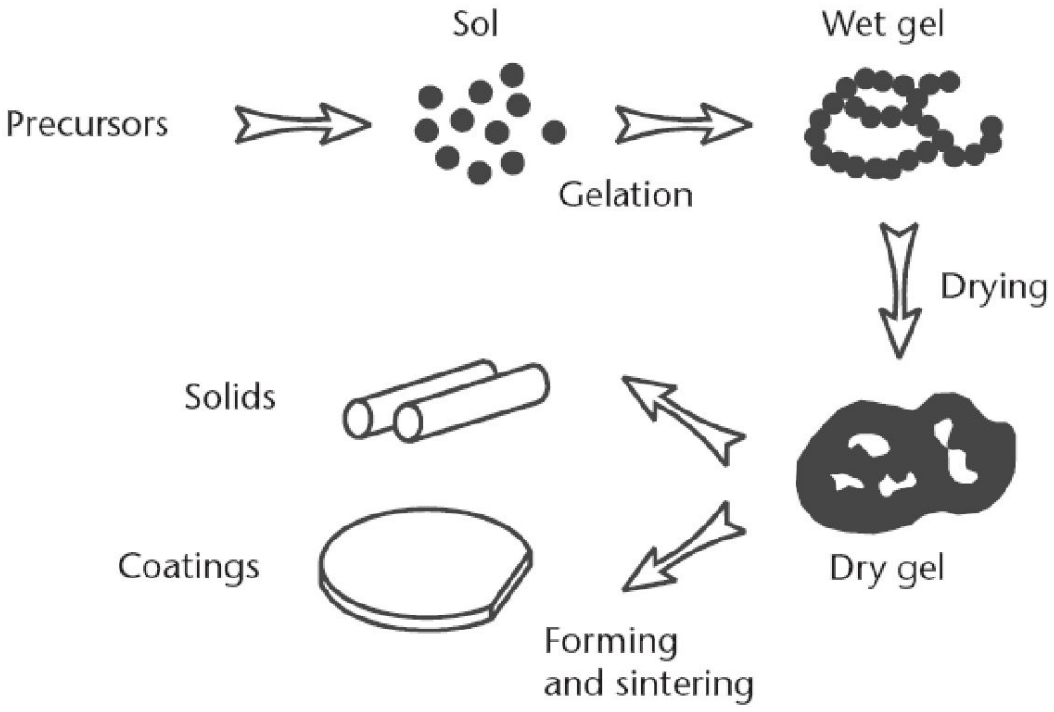
Отжиг при 800-1100 °C и формирование связей по реакции.
Annealing and bonding in accord to the chemical reaction

$$\mathrm{Si-O-H\bullet\bullet\bullet H-O-Si \rightarrow Si-O-Si + H_2O}$$

Химико-механическая полировка
Chemical-mechanical polishing

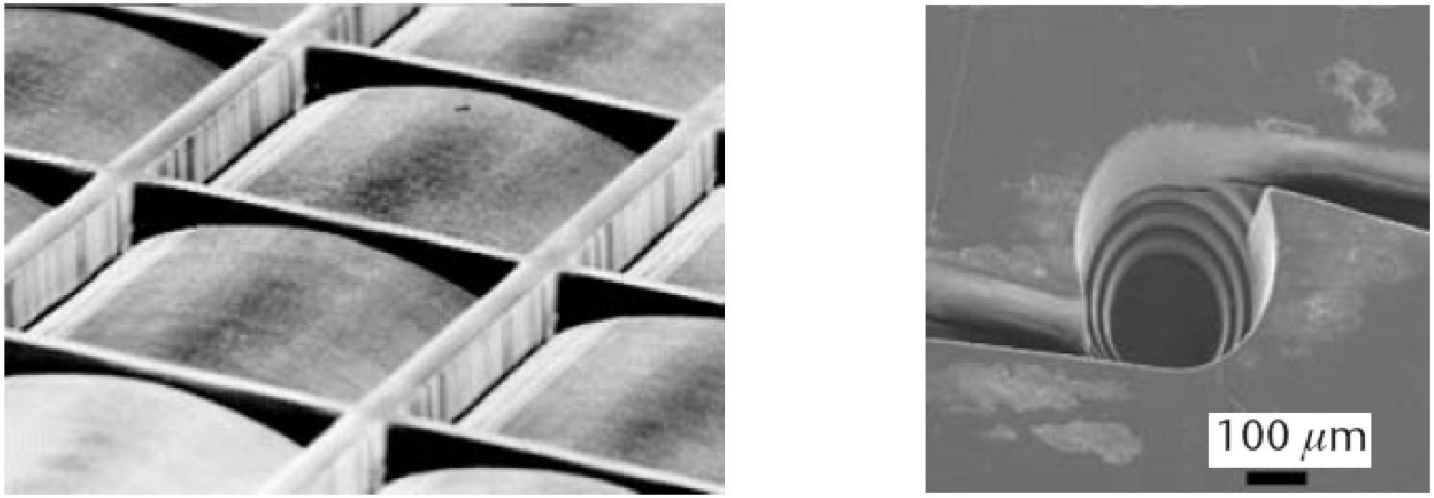


Sol-gel deposition



Материалы: силикон, оксид титана, алюминий, нитрид кремния и др.

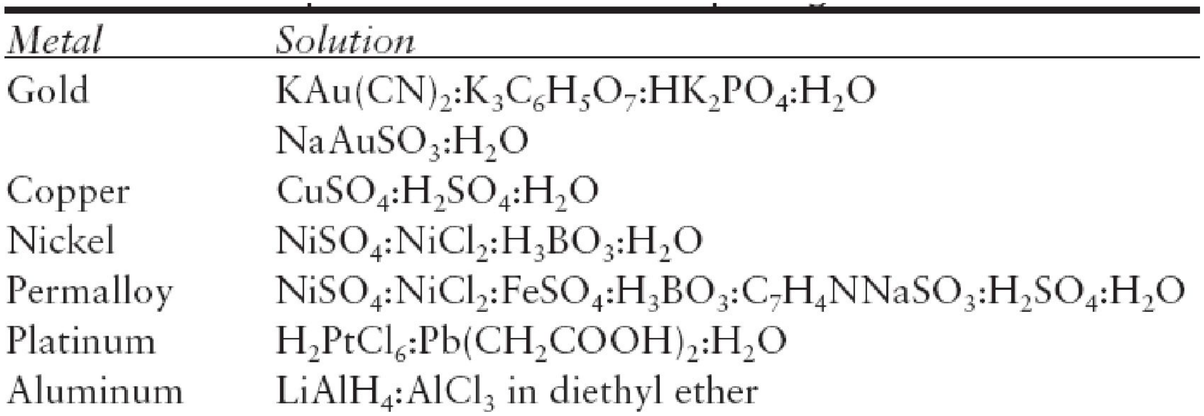
Лазерная обработка Laser machining



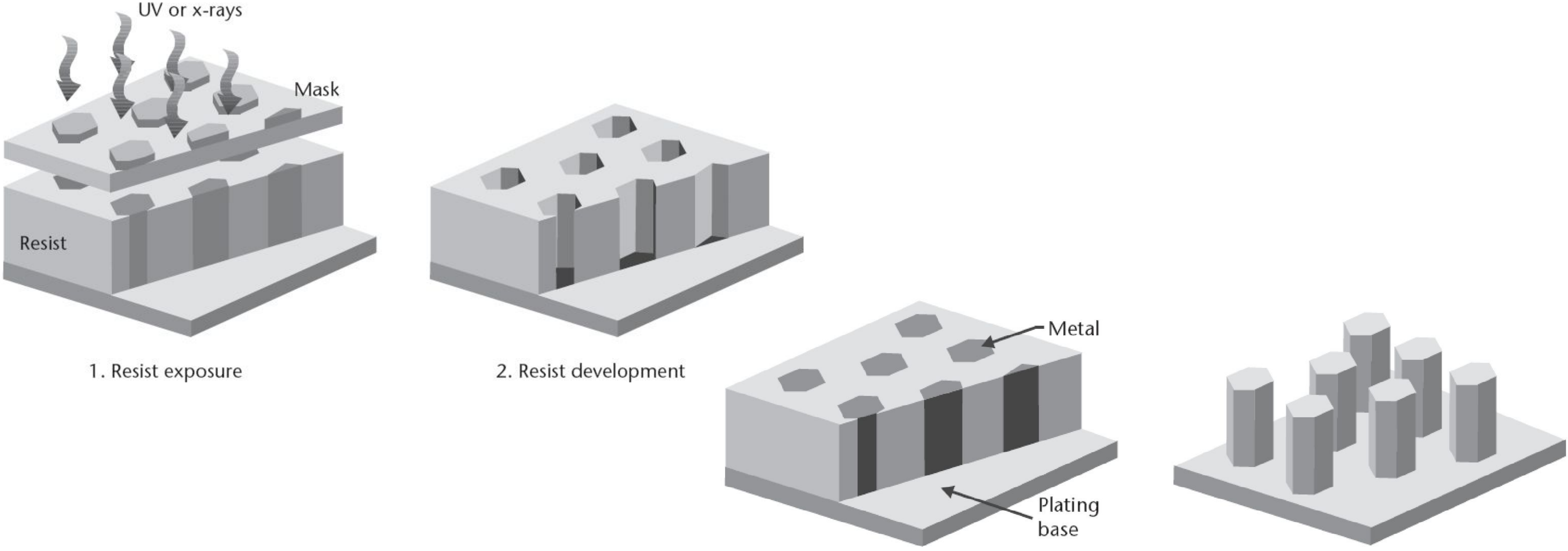
(a) (b)

Laser machining examples: (a) microlenses in polycarbonate; and (b) fluid-flow device in plastic. Multiple depths of material can be removed. (*Courtesy of:* Exitech Ltd., Oxford, United Kingdom.)

Гальваническое осаждение. Galvanic deposition.



Metal	*Solution*
Gold	$KAu(CN)_2$:$K_3C_6H_5O_7$:HK_2PO_4:H_2O
	$NaAuSO_3$:H_2O
Copper	$CuSO_4$:H_2SO_4:H_2O
Nickel	$NiSO_4$:$NiCl_2$:H_3BO_3:H_2O
Permalloy	$NiSO_4$:$NiCl_2$:$FeSO_4$:H_3BO_3:$C_7H_4NNaSO_3$:H_2SO_4:H_2O
Platinum	H_2PtCl_6:$Pb(CH_2COOH)_2$:H_2O
Aluminum	$LiAlH_4$:$AlCl_3$ in diethyl ether



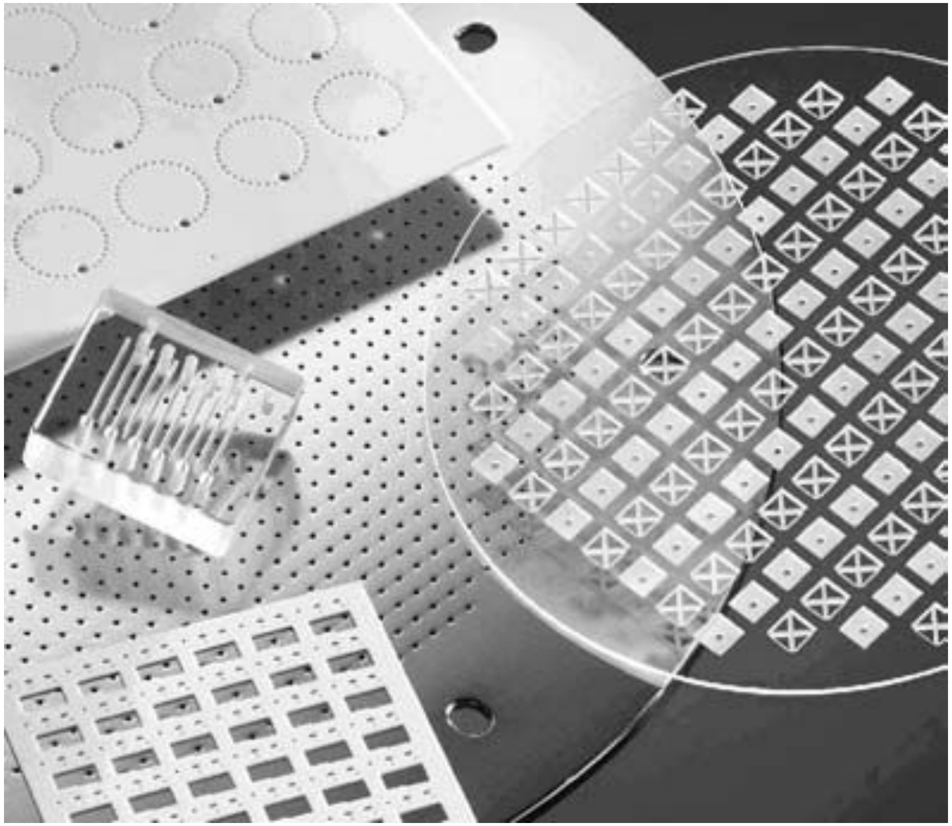
1. Resist exposure

2. Resist development

3. Electroplating

4. Removal of resist

Ультразвуковая шлифовка. Ultrasonic treatment.



Частота:
20-100 кГц

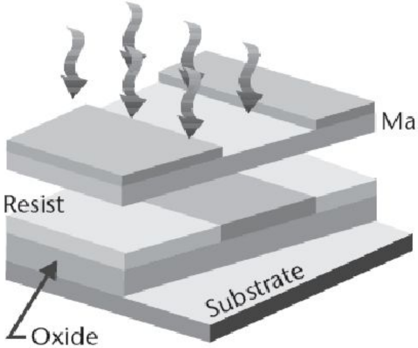
Растворители:
вода, масло

Абразивы:
BC, Al_2O_3, SiC

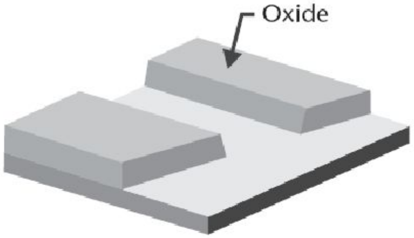
Размер отверстий
150 мкм – 100 мм

Photograph of ultrasonically drilled holes and cavities in glass (clear), alumina ceramic (white), and silicon (shiny). All of the holes in a single substrate are drilled simultaneously.
(*Courtesy of:* Bullen Ultrasonics, Inc., of Eaton, Ohio.)

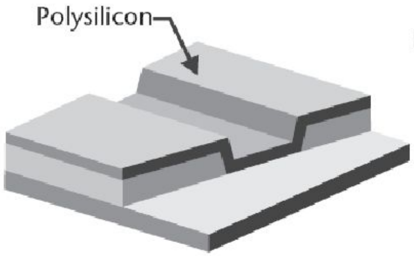
Цикл формирования НЭМС. Example



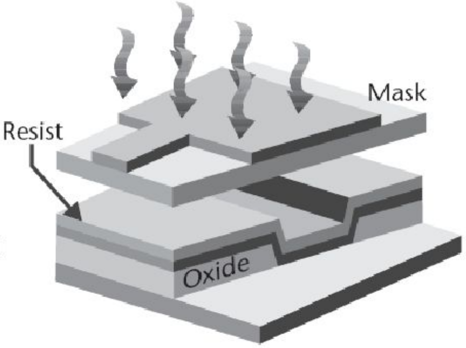
1. Resist exposure



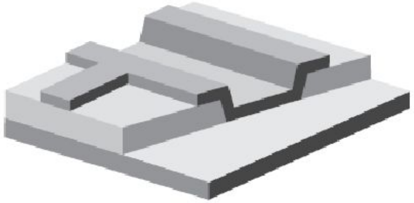
2. Resist development and oxide etch



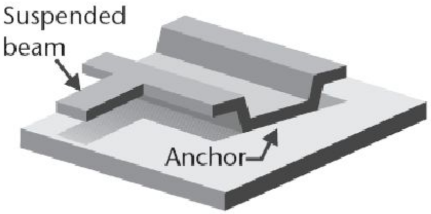
3. Deposition of polysilicon



4. Resist exposure

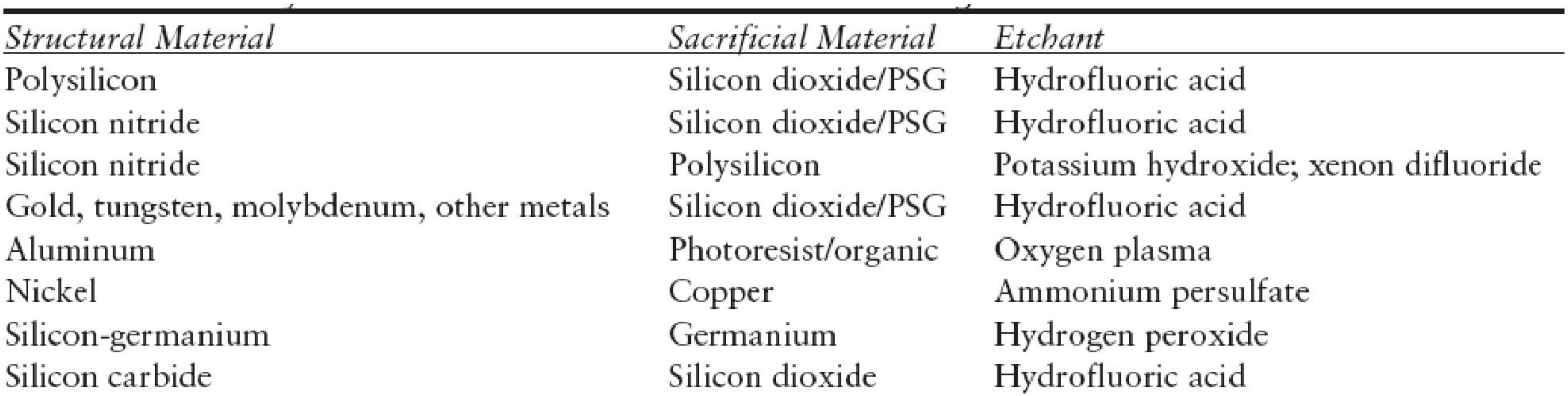


5. Resist development and polysilicon etch



6. Sacrificial etching of oxide

Некоторые пары конструкционных и вспомогательных материалов МЭМС. Structural and sacrificial materials.

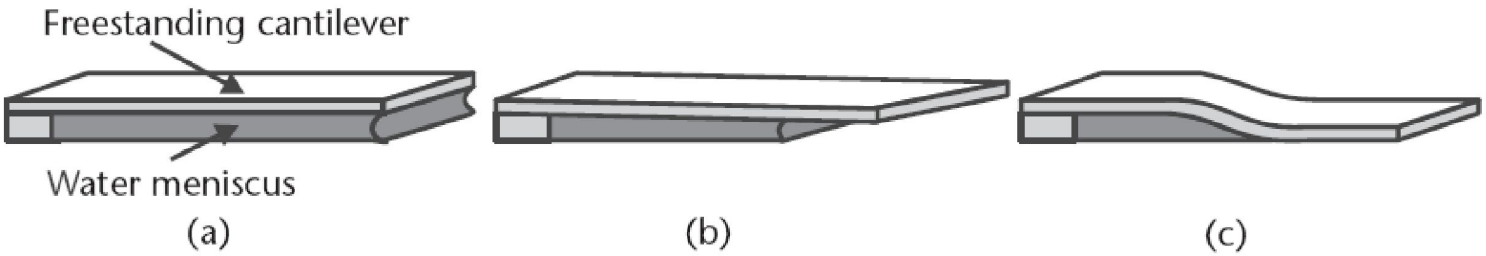


Structural Material	*Sacrificial Material*	*Etchant*
Polysilicon	Silicon dioxide/PSG	Hydrofluoric acid
Silicon nitride	Silicon dioxide/PSG	Hydrofluoric acid
Silicon nitride	Polysilicon	Potassium hydroxide; xenon difluoride
Gold, tungsten, molybdenum, other metals	Silicon dioxide/PSG	Hydrofluoric acid
Aluminum	Photoresist/organic	Oxygen plasma
Nickel	Copper	Ammonium persulfate
Silicon-germanium	Germanium	Hydrogen peroxide
Silicon carbide	Silicon dioxide	Hydrofluoric acid

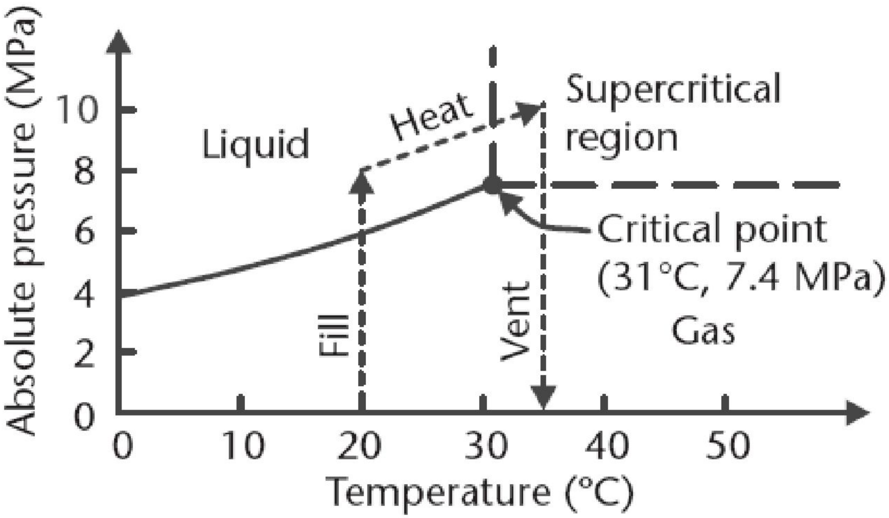
Травитель удаляет вспомогательный материал не разрушая конструкционный материал

PSG – стекло SiO_2:P

Закритическое высушивание. Supercritical drying.



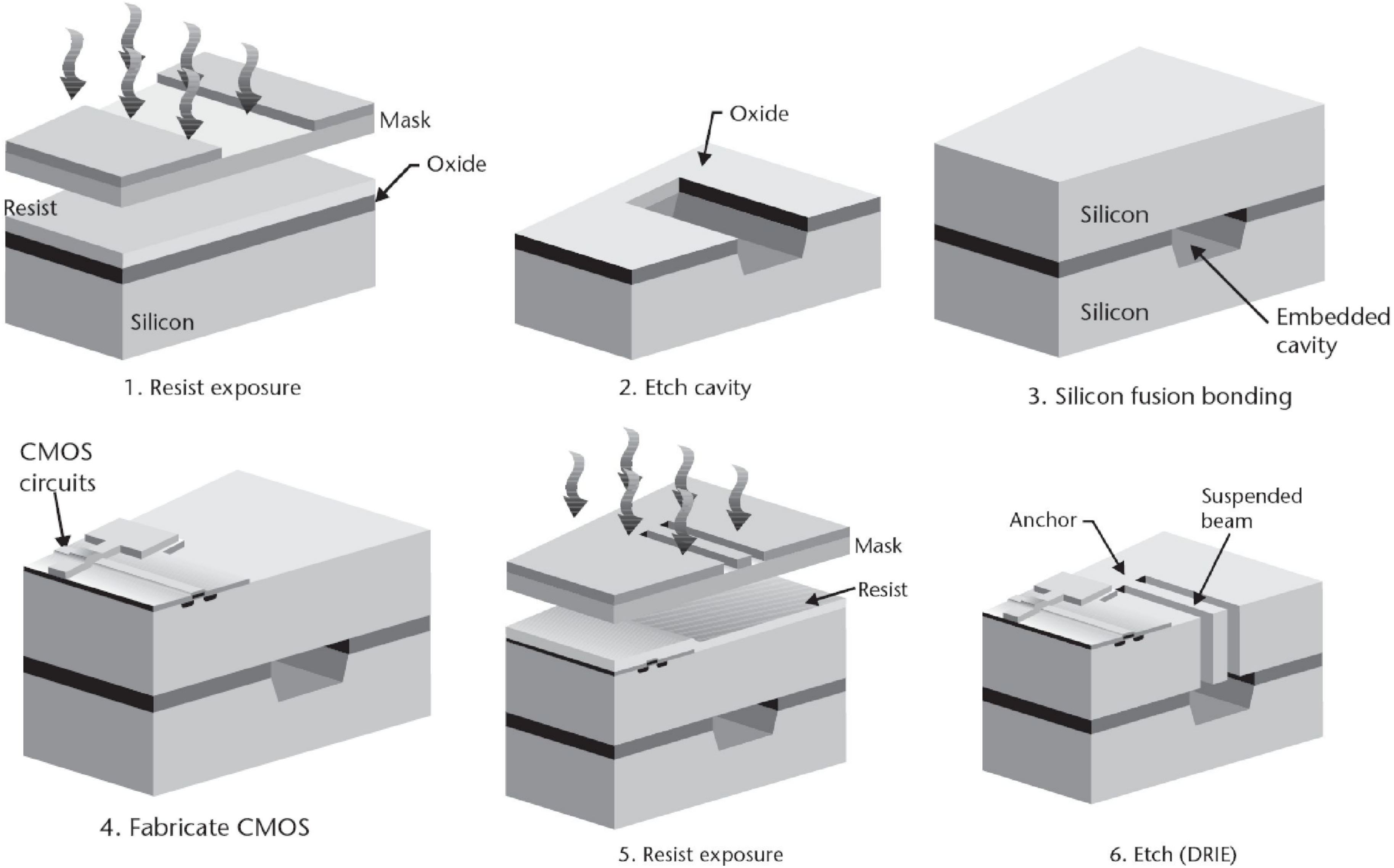
Pull-down of a compliant freestanding structure (a cantilever) due to surface tension during drying: (a) water completely fills the volume under the structure; (b) part of the water volume has dried; and (c) most of the water volume has dried, with surface tension pulling the structure down until it touches the substrate.



Цикл сушки:

1. Помещение в метанол, удаление воды
2. Закачка жидкого CO_2 под давлением, замещение метанола
3. Нагрев и переход в закритическую область
4. Снижение давления, удаление CO_2 газа

Комбинирование сращивания и DRIE
Combination of bonding and DRIE



1. Resist exposure

2. Etch cavity

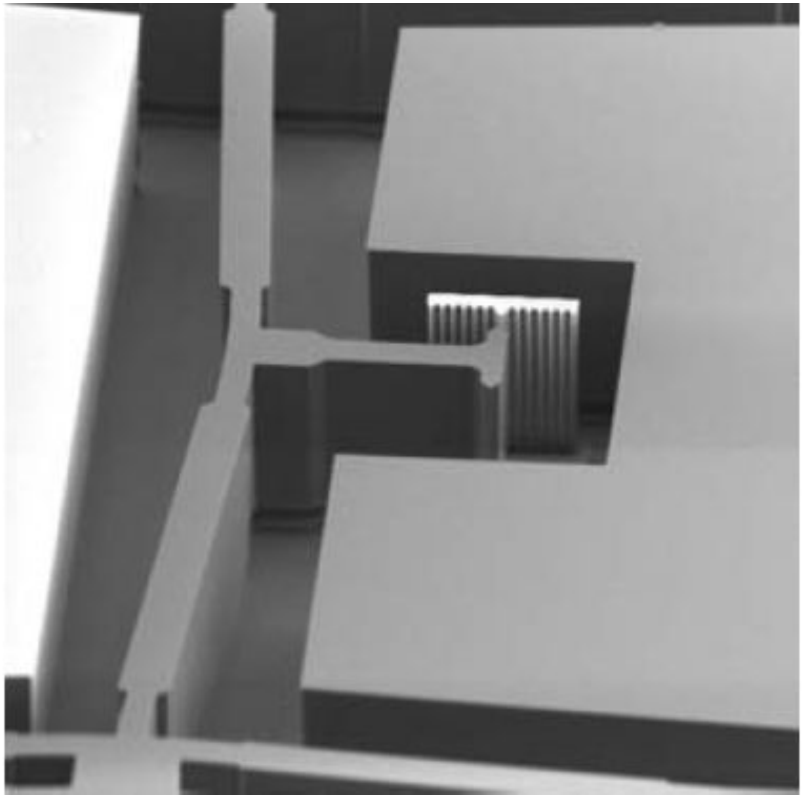
3. Silicon fusion bonding

4. Fabricate CMOS

5. Resist exposure

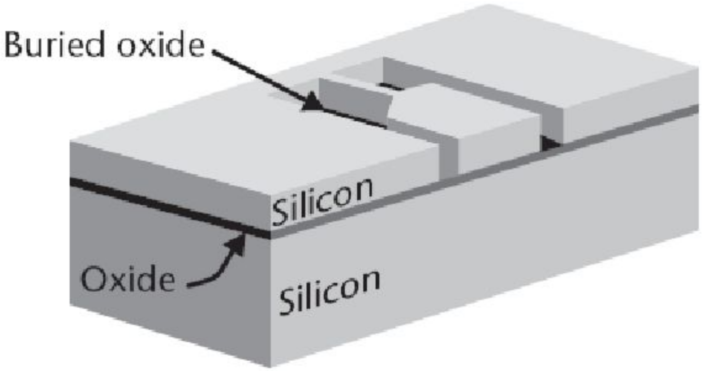
6. Etch (DRIE)

Комбинирование сращивания и DRIE
Combination of bonding and DRIE

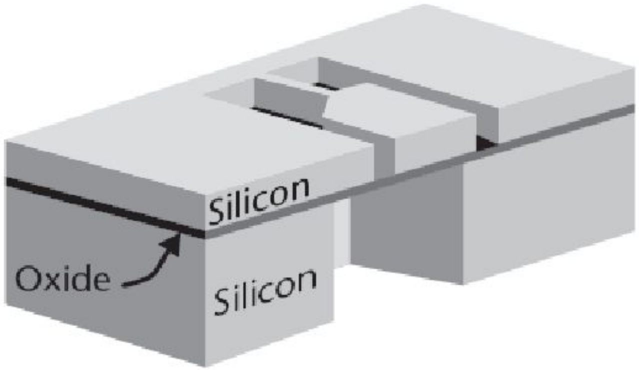


Scanning electron microscope image of a 200-μm-deep thermal actuator fabricated using silicon fusion bonding and DRIE. (*Courtesy of:* GE NovaSensor of Fremont, California.)

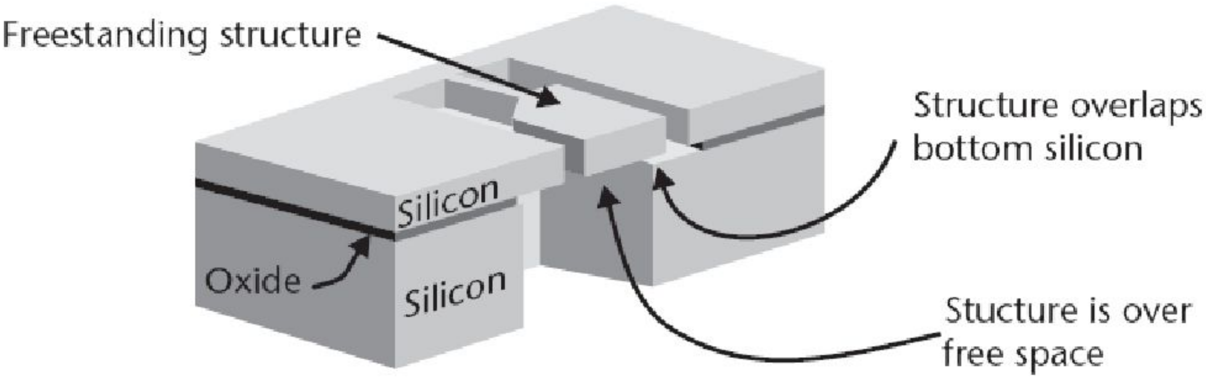
Комбинирование Combination SOI - DRIE



1. DRIE top side of SOI wafer stopping on oxide.

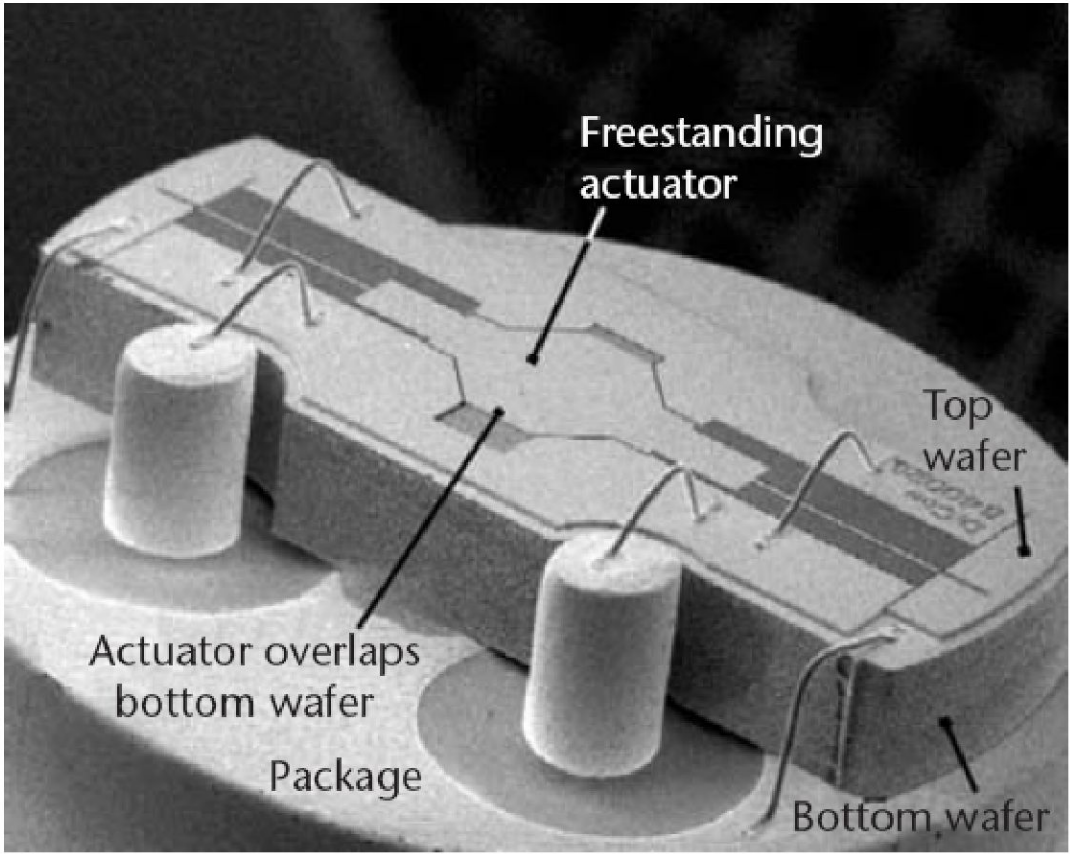


2. Double-sided alignment. DRIE back side of SOI wafer stopping on oxide.



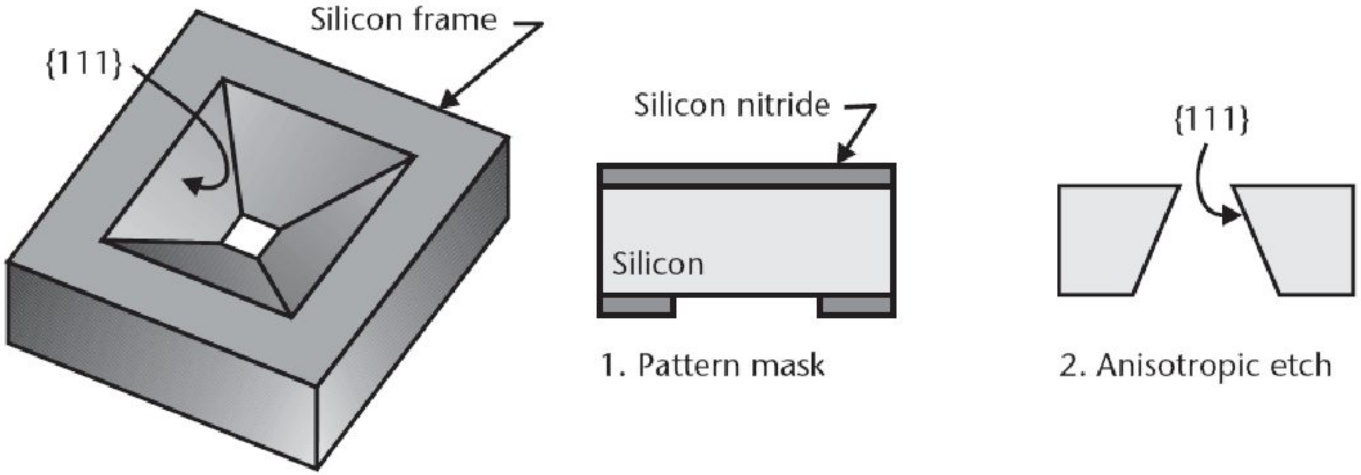
3. Etch buried oxide in HF

Комбинирование Combination SOI - DRIE



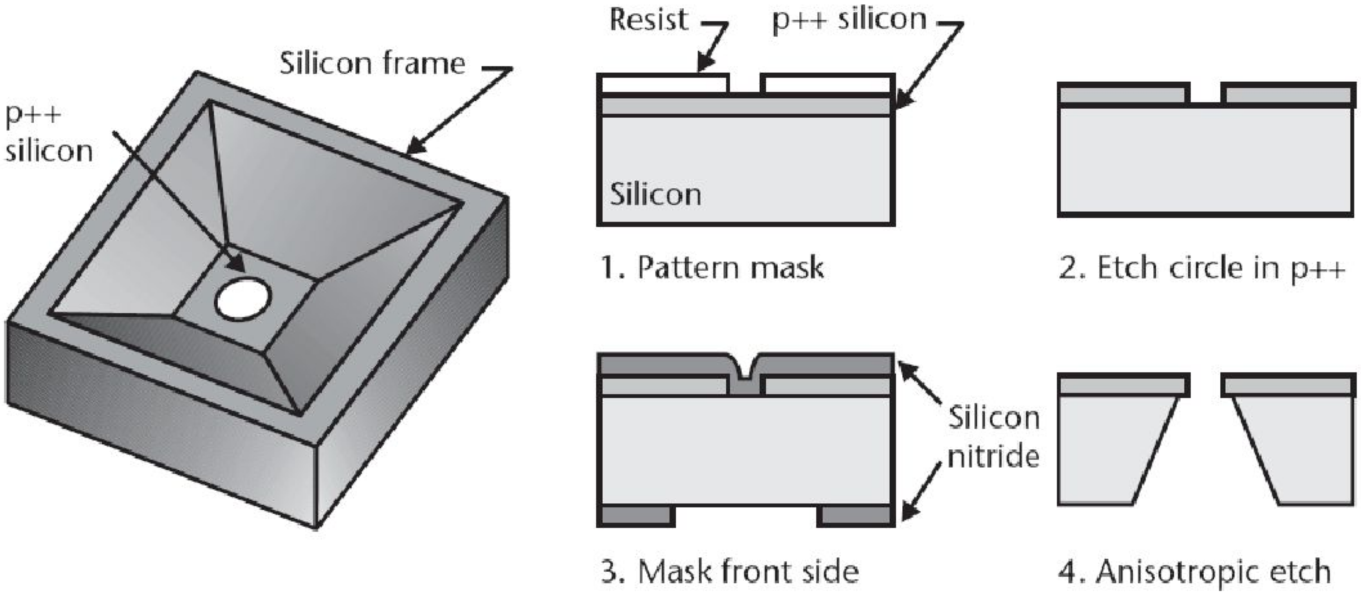
Scanning electron microscope image of a variable optical attenuator made by DRIE of a SOI wafer. (*Courtesy of:* DiCon Fiberoptics, Inc., of Richmond, California.)

Микро- и нано-сопла для струйных принтеров и систем инжекции топлива. Micro/nano-nozzles.



1. Pattern mask

2. Anisotropic etch



1. Pattern mask

2. Etch circle in p++

3. Mask front side

4. Anisotropic etch

Микро- и нано-сопла с боковым выходом.
Micro/nano-nozzles and channels.

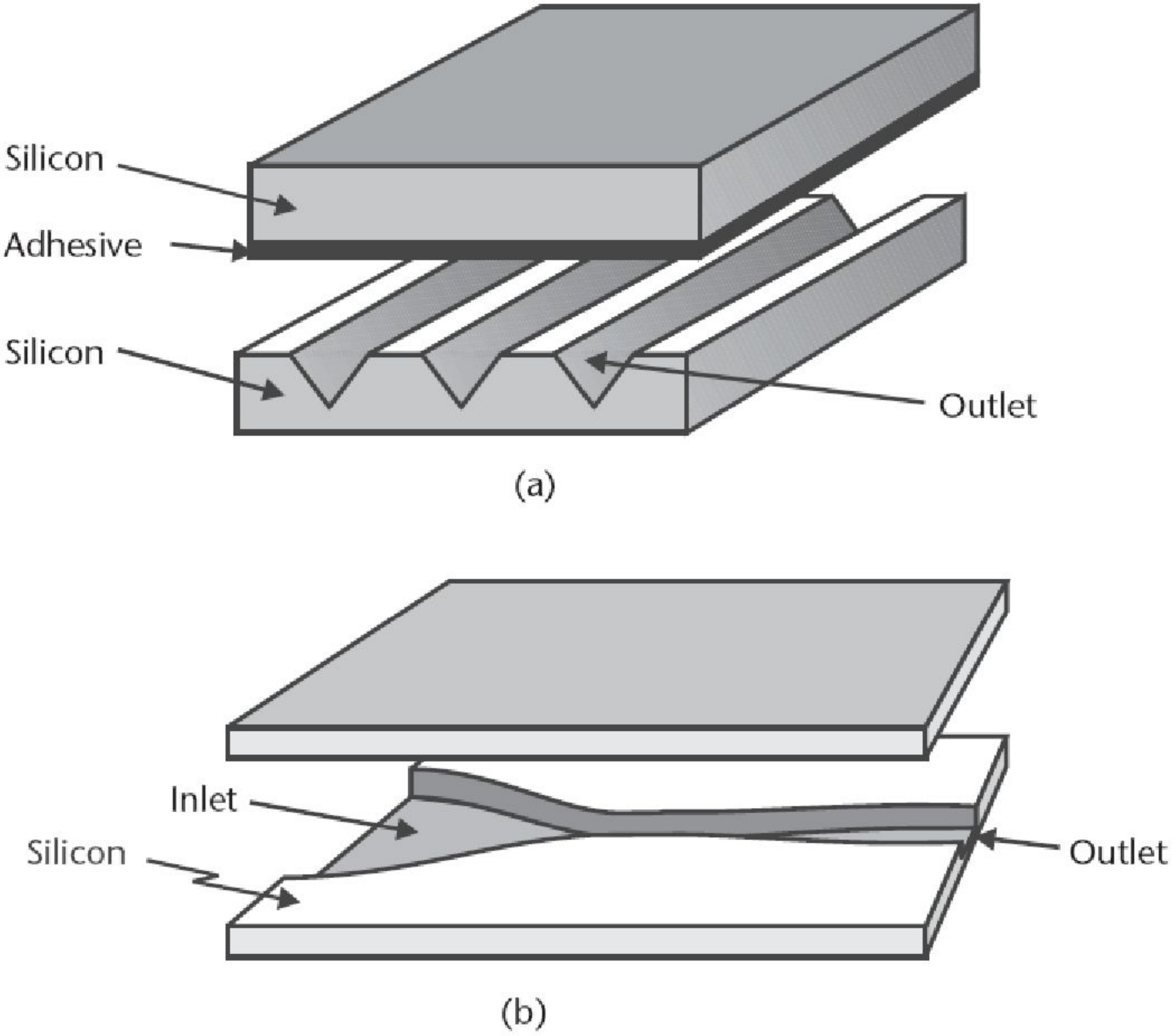
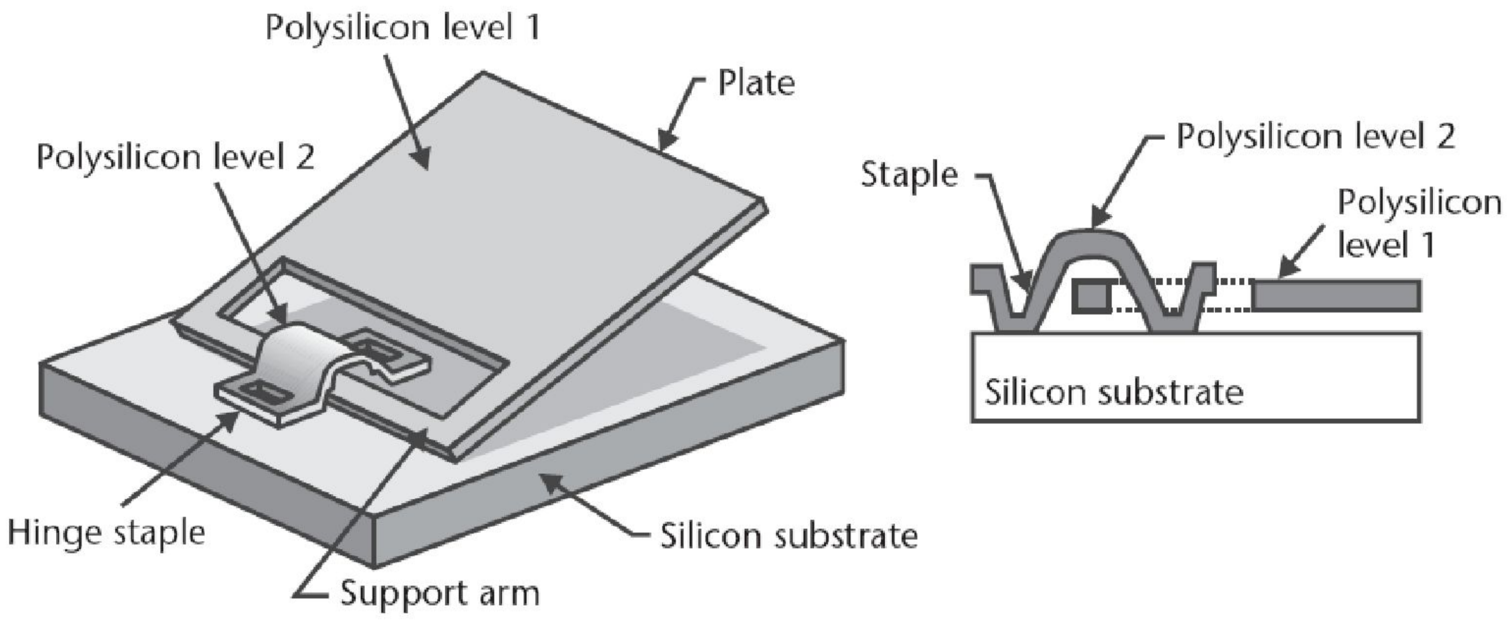


Illustration of side-shooter nozzles: (a) nozzles formed by orientation-dependent etching of grooves, wafer bonding, and dicing, and (b) nozzle formed by DRIE and wafer bonding.

Наношарниры Nanohinge



Домашнее задание Homework 10

Разработать пошаговую технологию создания шарнира для НЭМС/МЭМС
Develop step-by-step technology for a nanohinge.