Наномеханика

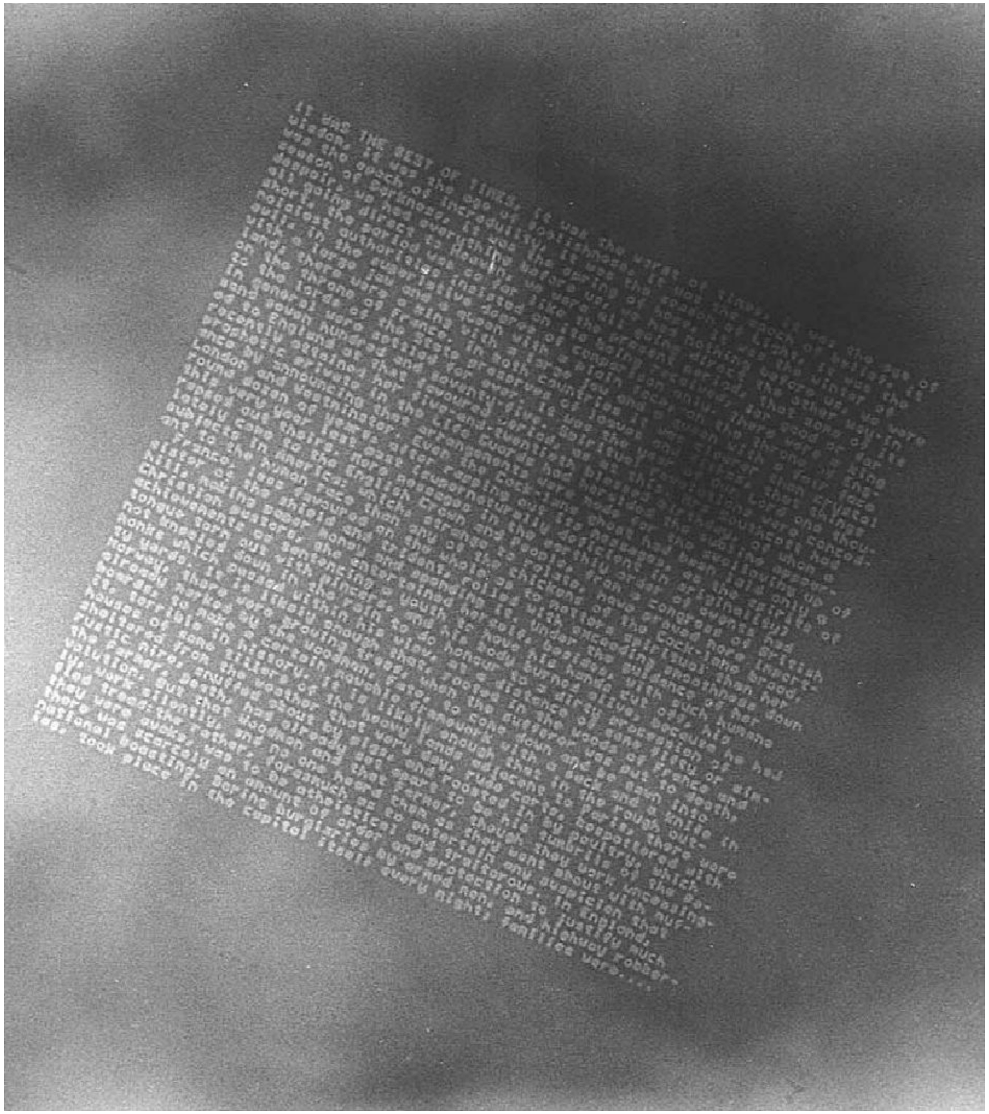
Nanomechanics of materials and systems

Лекция 11

Материалы и технологии изготовления
нано- и микро-электромеханических систем
НЭМС/МЭМС

Materials and technologies of nano- and
micro-electro-mechanical systems
NEMS/MEMS

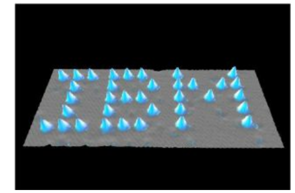
Хранение информации. Information memory.



“It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness…” from *A Tale of Two Cities* by Charles Dickens, engraved on a thin silicon nitride membrane. The entire page measures a mere 5.9 μm on a side, sufficiently small that 60,000 pages—equivalent to the *Encyclopedia Britannica*—can fit on a pinhead. The work, by T. Newman and R. F. W. Pease of Stanford University, won the Feynman challenge in 1985.

(*Courtesy of: Engineering & Science*, California Institute of Technology, Pasadena, California.)

Устройства памяти



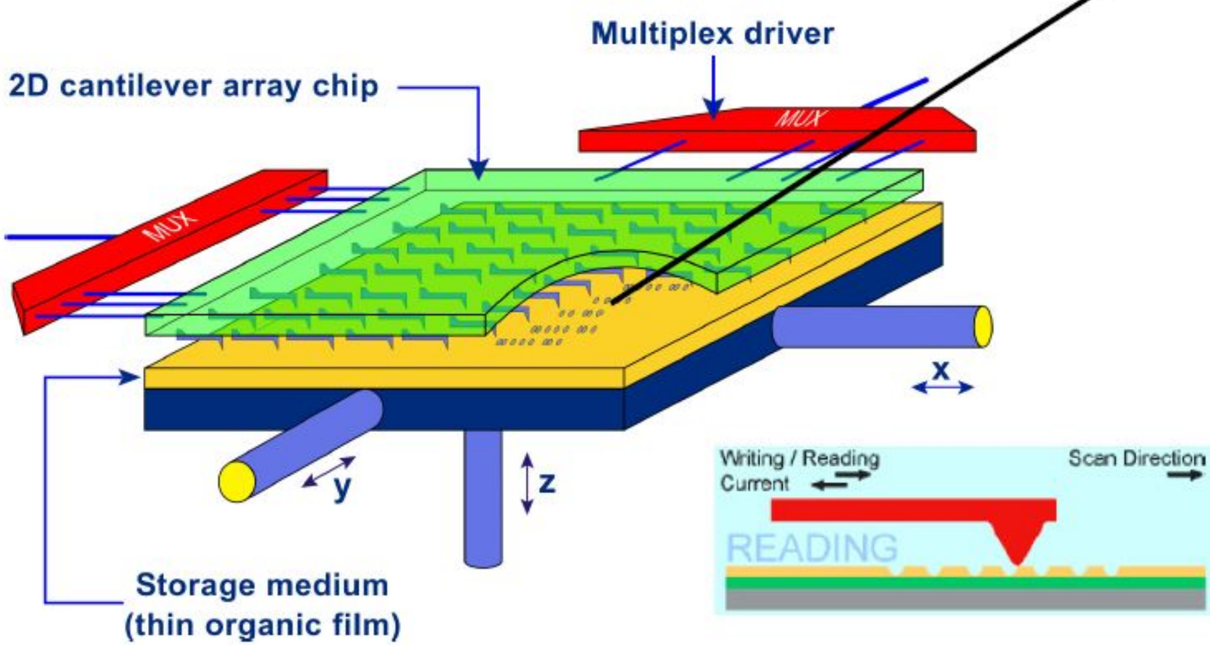
35 Xe atoms

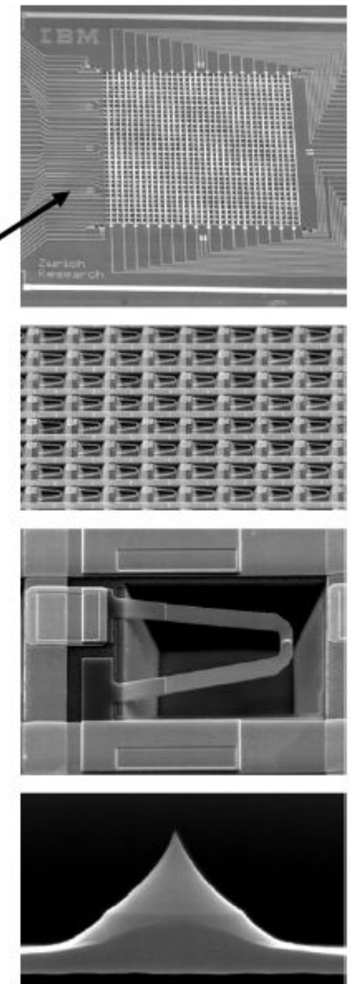
MEMS Memory: IBM's Millipede

Array of AFM tips write and read bits:
potential for low and adaptive power

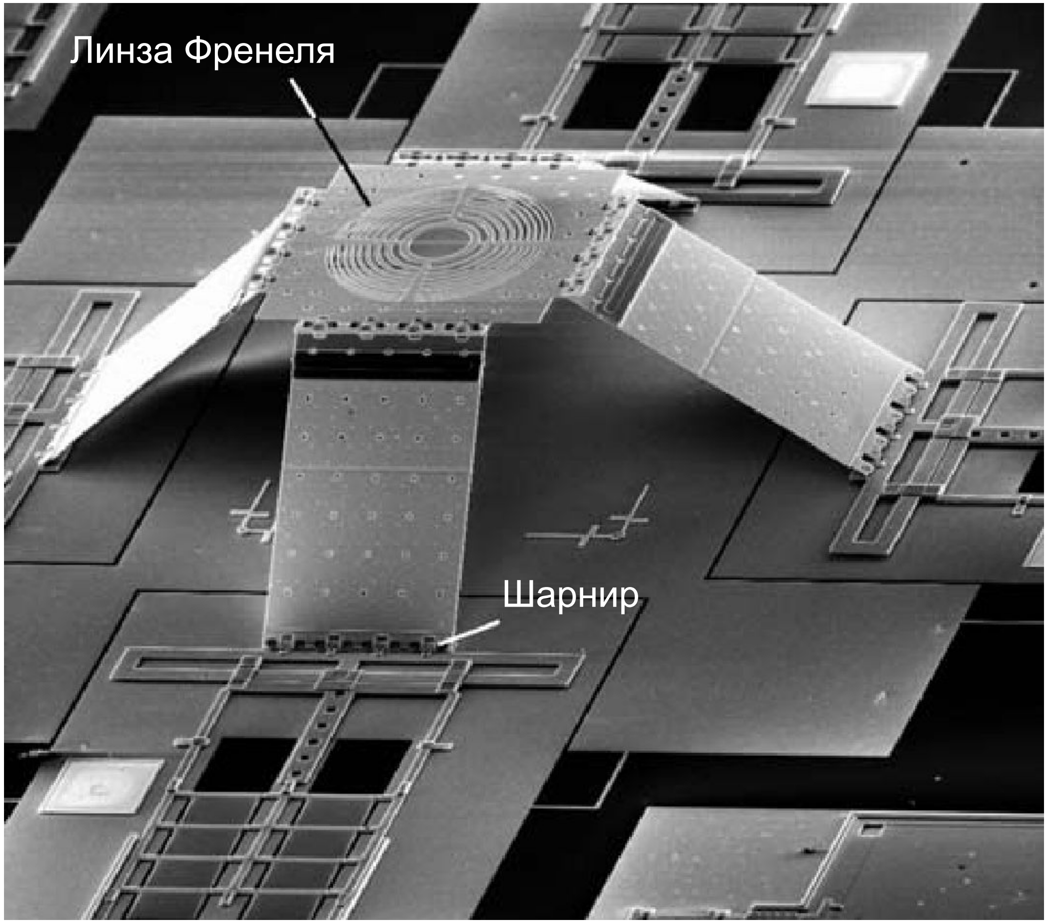
"MILLIPEDE"

Highly parallel, very dense AFM data storage system



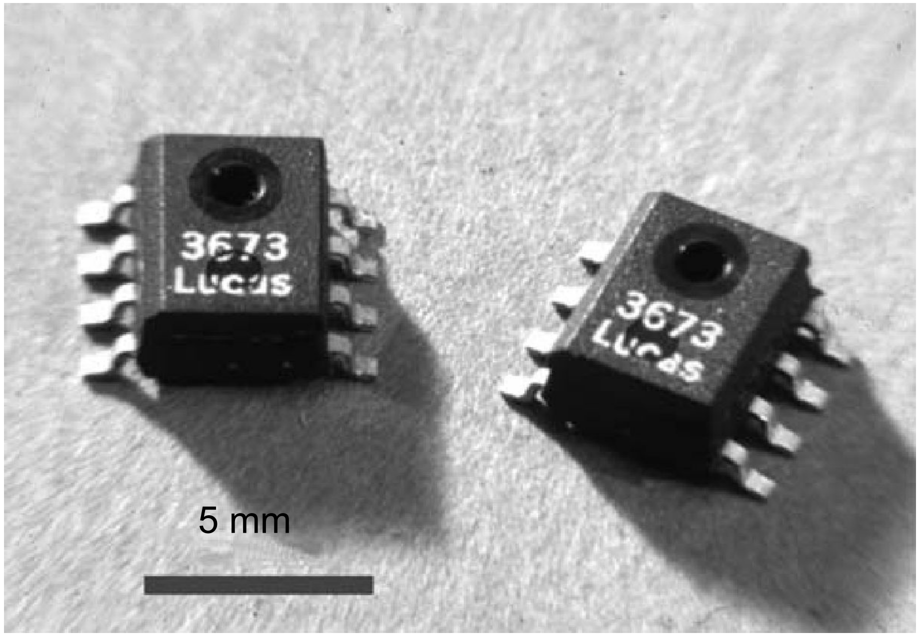


Оптическая система. Optical system.



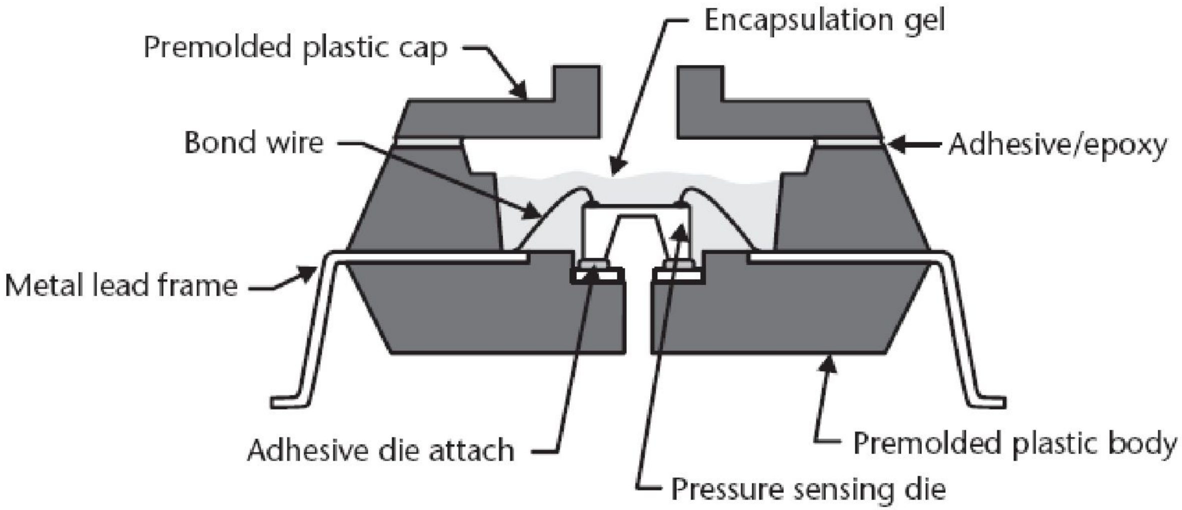
Photograph of a Fresnel microlens on an adjustable platform made of five hinged polysilicon plates. (*Courtesy of*: M. Wu, University of California, Los Angeles.)

Датчик давления. Pressure sensor.

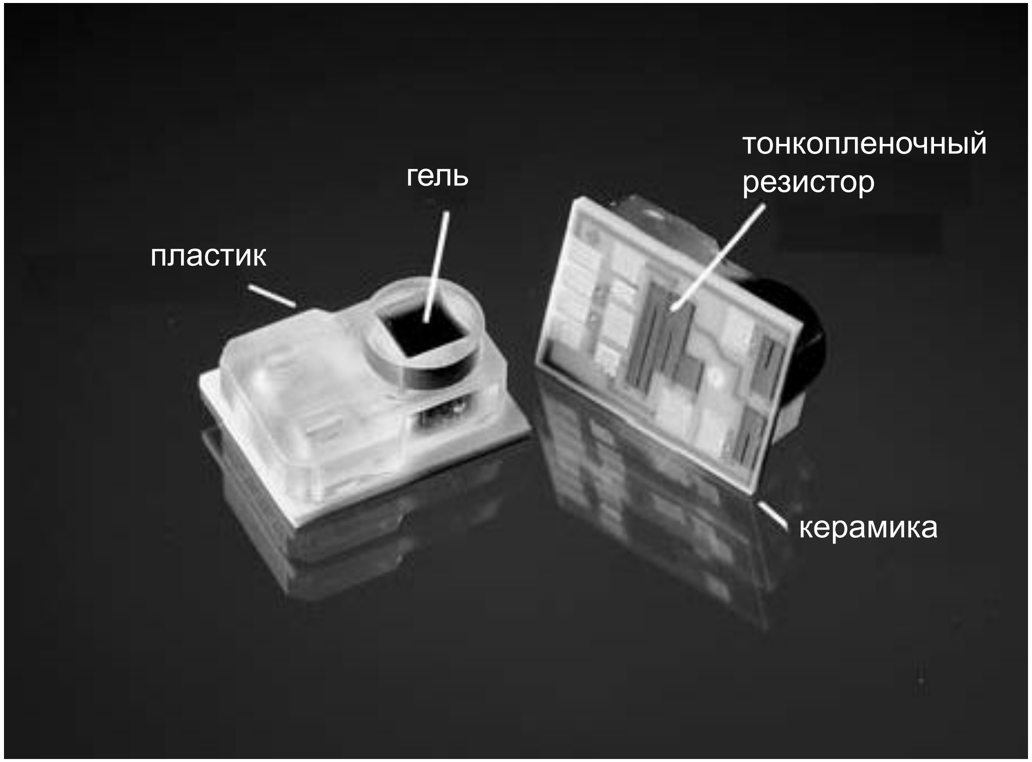


Photograph of the NovaSensor NPP-301, a premolded plastic, surface mount (SOIC-type) and absolute pressure sensor. (*Courtesy of:* GE NovaSensor of Fremont, California.)

Illustration of a premolded plastic package. Adapting it to pressure sensors involves incorporating fluid ports in the premolded plastic housing and the cap.



Датчик кровяного давления. Blood pressure sensor.



Photograph of a disposable blood pressure sensor for arterial-line measurement in intensive care units. The die (not visible) sits on a ceramic substrate and is covered with a plastic cap that includes an access opening for pressure. A special black gel dispensed inside the opening protects the silicon device while permitting the transmission of pressure. (*Courtesy of:* GE NovaSensor, Fremont, California .)

Преимущества Si как базового материала НЭМС
Advantages of Si in NEMS/MEMS

- Дешевизна. Cheap.
- Высокое кристаллическое совершенство. High crystalline quality.
- Возможность создания гетероструктур с SiO, SiN, SiC, металлами (Al, Ti, W, Cu, и др.), полимерами и т.д. Heterostructures with SiO, SiN, SiC, Al, Ti, W, Cu, polymers, etc.
- Хорошие механические и термические свойства. Good mechanical properties.
- Электрические свойства, изменяемые в широком диапазоне. Widely tunable electrical properties.
- Возможность интеграции с микроэлектронными приборами в одном чипе. Integration of MEMS and microelectronics in a chip.
- Наличие монокристаллической, аморфной и поликристаллической форм. Set of monocrystalline, amorphous and polycrystalline forms.
- Химическая стабильность, нетоксичность. Chemical stability, non-toxic.
- Наличие разработанных технологий и технологического оборудования. Availability of well developed technology and equipment.

Формы и содинения кремния. Si forms and compounds.

- **Crystalline silicon** is a hard and brittle material deforming elastically until itreaches its yield strength, at which point it breaks. Its tensile yield strength is 7 GPa,which is equivalent to a 700-kg weight suspended from a 1-mm^2 area. Its Young’s modulus is dependent on crystal orientation, being 169 GPa in <110> directions and 130 GPa in <100> directions—near that of steel. Silicon is a very good thermal conductor with a thermal conductivity greater than that of many metals and approximately 100 times larger than that of glass. In complex integrated systems, the silicon substrate can be used as an efficient heat sink.
- The mechanical properties of **polycrystalline and amorphous silicon** vary with deposition conditions, but, by and large, they are similar to that of single crystal silicon. Both normally have relatively high levels of intrinsic stress (hundreds of MPa) after deposition, which requires annealing at elevated temperatures (>900ºC).
- Silicon is such a successful material because it has a stable oxide that is electrically insulating—unlike germanium, whose oxide is soluble in water, or gallium arsenide, whose oxide cannot be grown appreciably. Various forms of **silicon oxides** (SiO_2, SiO_x, silicate glass) are widely used in micromachining due to their excellent electrical and thermal insulating properties.
- **Silicon nitride** (Si_xN_y) is also a widely used insulating thin film and is effective as a barrier against mobile ion diffusion—in particular, sodium and potassium ions found in biological environments. Its Young’s modulus is higher than that of silicon and its intrinsic stress can be controlled by the specifics of the deposition process. Silicon nitride is an effective masking material in many alkaline etch solutions.

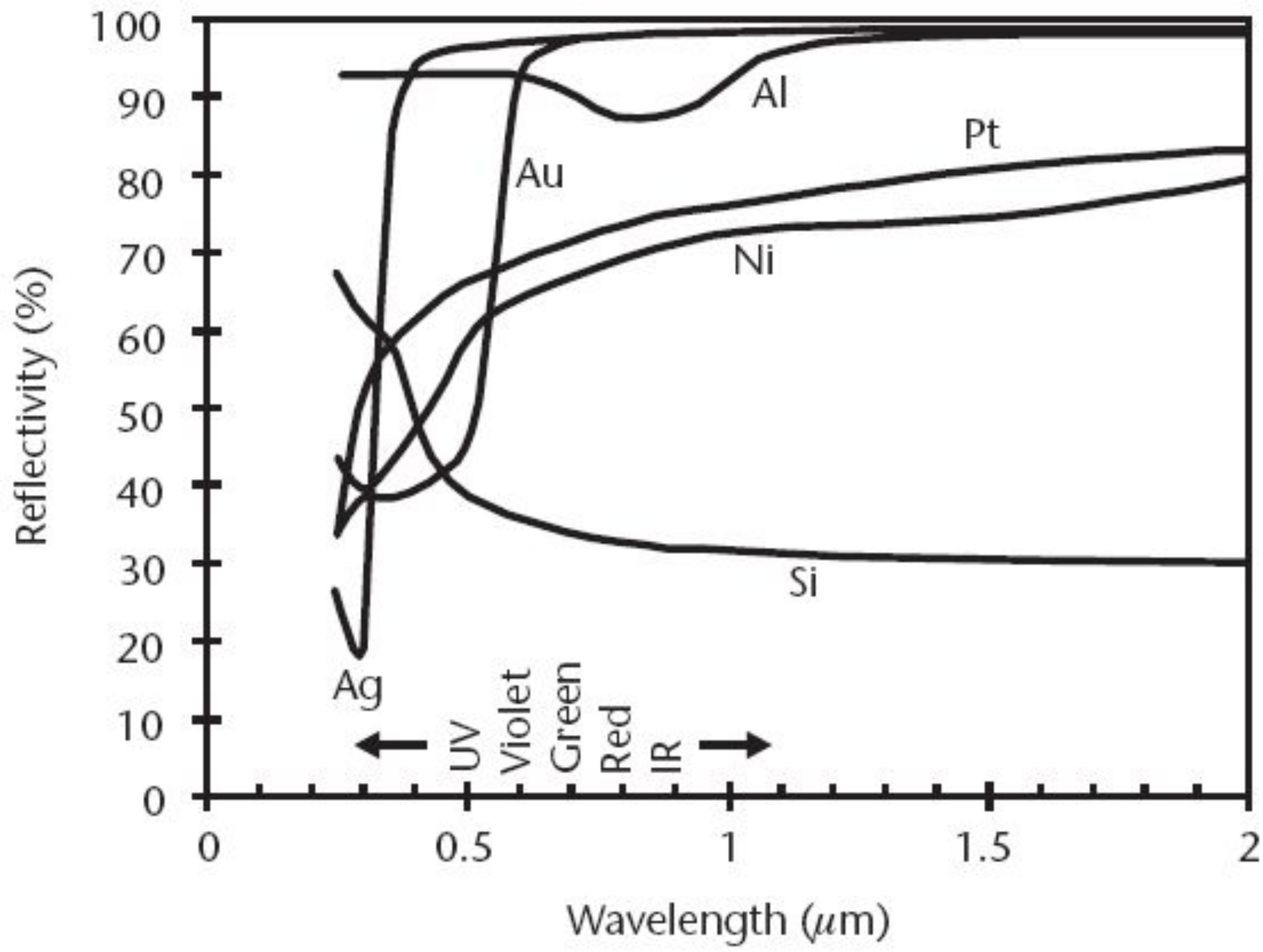
Физические свойства некоторых материалов НЭМС

Property[a]	Si	SiO_2	Si_3N_4	Quartz	SiC	Diamond	GaAs	AlN	92% Al_2O_3	Polyimide	PMMA
Relative permittivity (ε_r)	11.7	3.9	4–8	3.75	9.7	5.7	13.1	8.5	9	—	—
Dielectric strength (V/cm $\times 10^6$)	0.3	5–10	5–10	25–40	4	10	0.35	13	11.6	1.5–3	0.17
Electron mobility (cm^2/V·s)	1,500	—	—	—	1,000	2,200	8,800	—	—	—	—
Hole mobility (cm^2/V·s)	400	—	—	—	40	1,600	400	—	—	—	—
Bandgap (eV)	1.12	8-9	—	—	2.3–3.2	5.5	1.42	—	—	—	—
Young's modulus (GPa)	160	73	323	107	450	1,035	75	340	275	2.5	3
Yield/fracture strength (GPa)	7	8.4	14	9	21	>1.2	3	16	15.4	0.23	0.06
Poisson's ratio	0.22	0.17	0.25	0.16	0.14	0.10		0.31	0.31	0.34	—
Density (g/cm^3)	2.4	2.2	3.1	2.65	3.2	3.5	5.3	3.26	3.62	1.42	1.3
Coefficient of thermal expansion (10^{-6}/°C)	2.6	0.55	2.8	0.55	4.2	1.0	5.9	4.0	6.57	20	70
Thermal conductivity at 300K (W/m·K)	157	1.4	19	1.4	500	990–2,000	0.46	160	36	0.12	0.2
Specific heat (J/g·K)	0.7	1.0	0.7	0.787	0.8	0.6	0.35	0.71	0.8	1.09	1.5
Melting temperature (°C)	1,415	1,700	1,800	1,610	1,800[b]	3,652[b]	1,237	2,470	1,800	380[c]	90[c]

Тонкие пленки металлов в НЭМС

Metal	*ρ (μΩ·cm)*	*Typical Areas of Application*
Ag	1.58	Electrochemistry
Al	2.7	Electrical interconnects; optical reflection in the visible and the infrared
Au	2.4	High-temperature electrical interconnects; optical reflection in the infrared; electrochemistry; corrosion-resistant contact; wetting layer for soldering
Cr	12.9	Intermediate adhesion layer
Cu	1.7	Low-resistivity electrical interconnects
Indium-tin oxide (ITO)	300–3,000	Transparent conductive layer for liquid crystal displays
Ir	5.1	Electrochemistry; microelectrodes for sensing biopotentials
Ni	6.8	Magnetic transducing; solderable layer
NiCr	200–500	Thin-film laser trimmed resistor; heating element
Pd	10.8	Electrochemistry; solder-wetting layer
Permalloy™ (Ni_xFe_y)	—	Magnetic transducing
Pt	10.6	Electrochemistry; microelectrodes for sensing biopotentials; solderable layer
SiCr	2,000	Thin-film laser trimmed resistor
SnO_2	5,000	Chemoresistance in gas sensors
TaN	300–500	Negative temperature coefficient of resistance (TCR) thin-film laser trimmed resistor
Ti	42	Intermediate adhesion layer
TiNi	80	Shape-memory alloy actuation
TiW	75–200	Intermediate adhesion layer; near zero TCR
W	5.5	High-temperature electrical interconnects; thermionic emitter

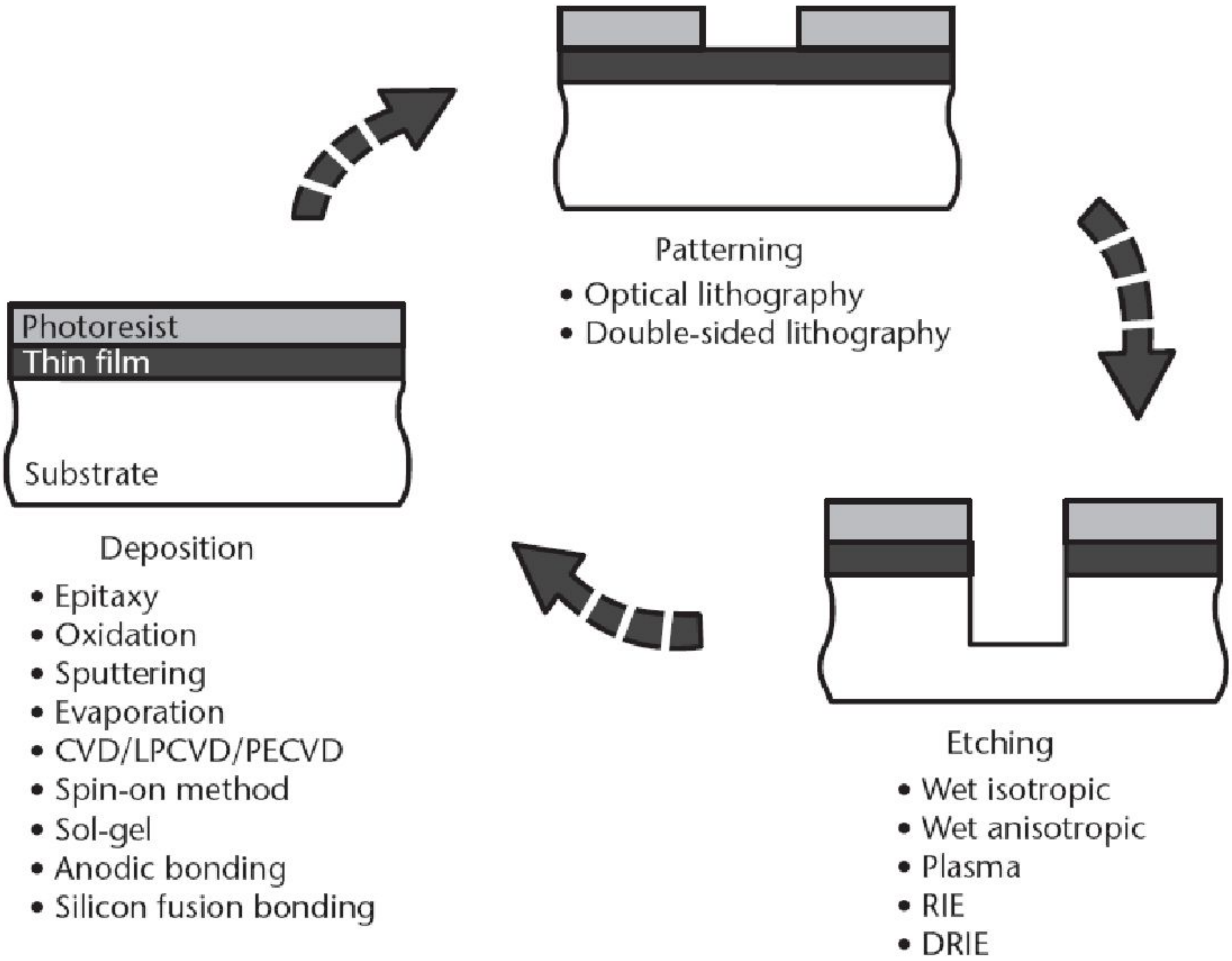
Оптическое отражение от кремния и некоторых металлов
Reflectivity of Si and some metals



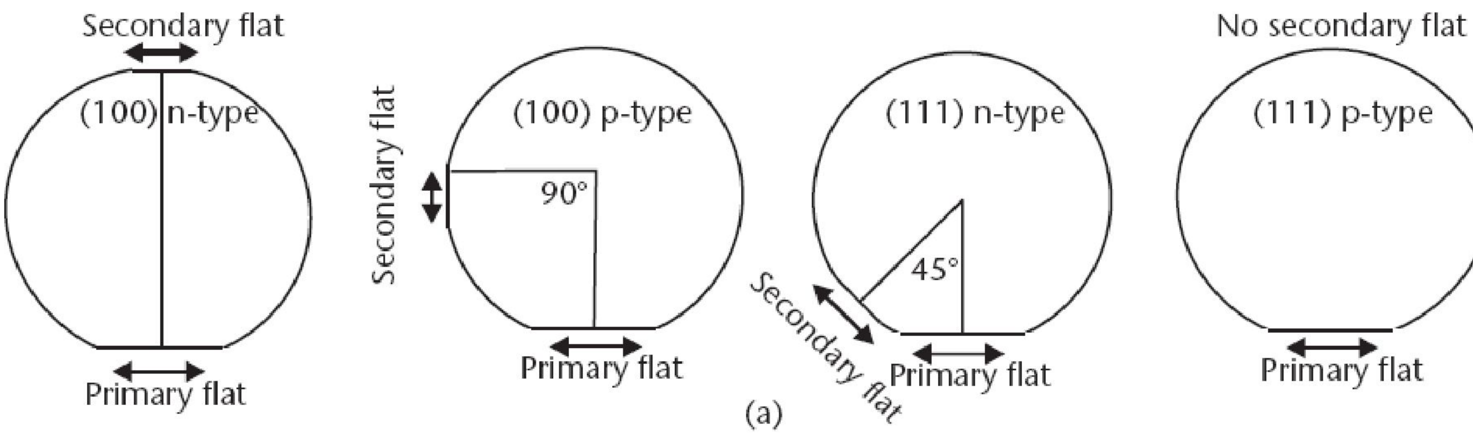
Области применения различных материалов в НЭМС.
Application areas of MEMS materials.

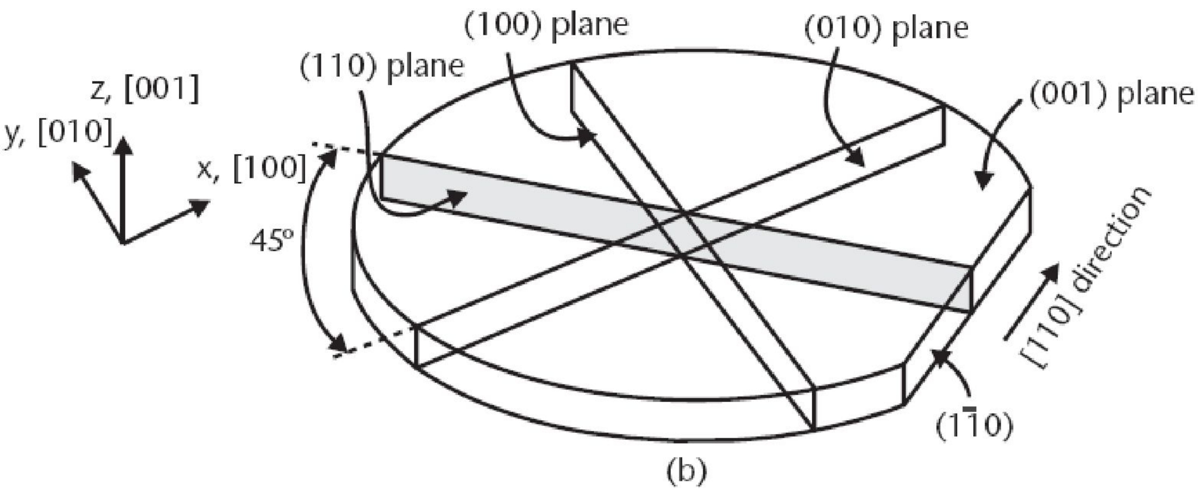
Si, SiO, SiN, поликремний poly-Si, аморфный amorphous-Si в сочетании с тонкими пленками металлов (thin metal films), полимерами (polymers) и стеклами (glasses).	Базовая группа материалов Base group
SiC и алмаз (SiC and diamond)	Высокие температуры (>500 C) и агрессивные среды High temperature and aggressive environment application
Соединения III-V-compounds	Интеграция с СВЧ и лазерными системами UHF devices, LED and lasers
Полимеры (ПММА, полимиды, поликарбонаты и др.) Polymers	“Мягкие” системы, форсунки, капилляры Soft systems
Сплавы с памятью формы Memory shape alloys (Ti-Ni, Cu-Al-Ni, Fe-Ni, Fe-Pt и др.)	Термо-актуаторы Thermoactuators

Базовый цикл создания НЭМС. Base cycle of NEMS formation.



Маркировка пластин полупроводников. Marking of wafers.





Стандарты размеров:
Standard sizes:

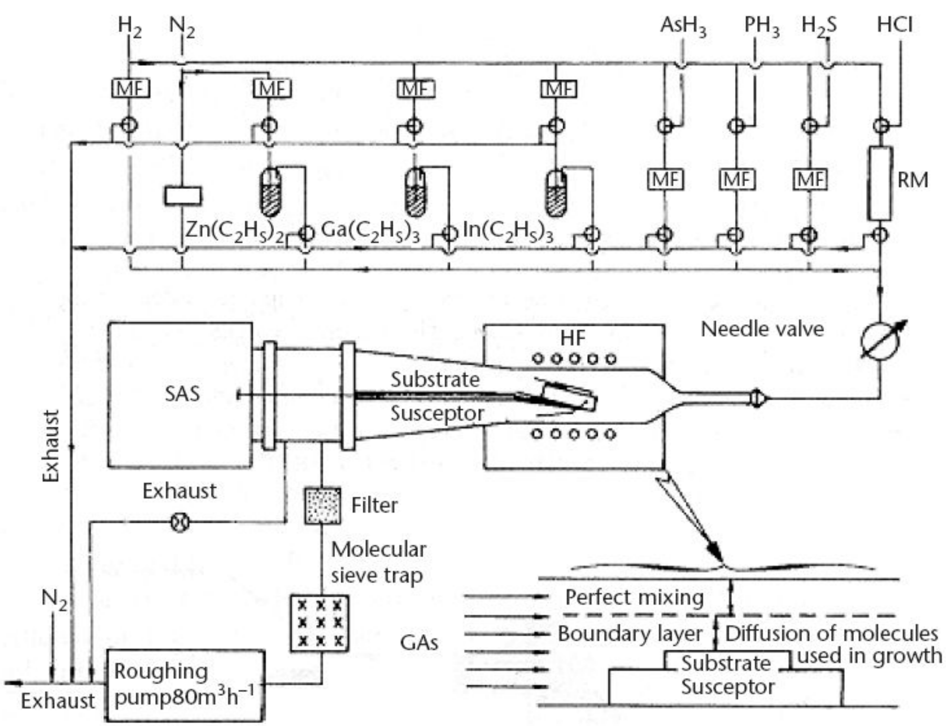
Диаметр 100 mm diameter
Толщина 525 μm thickness

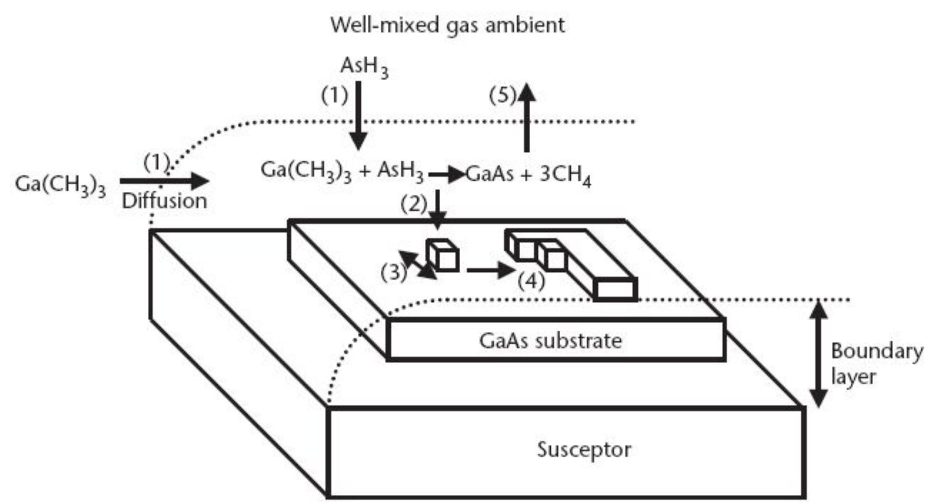
Диаметр 150 mm diameter
Толщина 625 μm thickness

(a) Illustration showing the primary and secondary flats of {100} and {111} wafers for both *n*-type and *p*-type doping (SEMI standard); (b) illustration identifying various planes in a wafer of {100} orientation (the wafer thickness is exaggerated);

Эпитаксия кремния – молекулярно-лучевая или газофазная
Epitaxy of Si – MBE and VPE

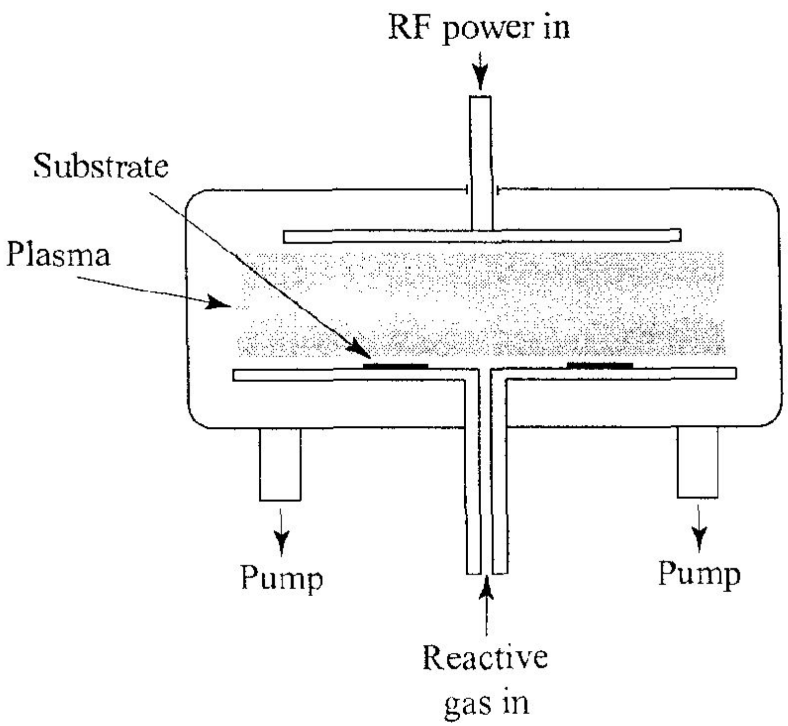
- Массовое промышленное производство пленок Si - газофазная эпитаксия. Vapor phase epitaxy (VPE) – mass production of Si.
- Temperature > 800 °C. Growth rate 0.2-4 μm/min.
- Si sources are SiH_4, $SiCl_4$, SiH_2Cl_2.
- Doping via AsH_3, PH_3 и B_2H_6.
- Substrates are Si (100 mm or 150 mm), sapphire in special cases.





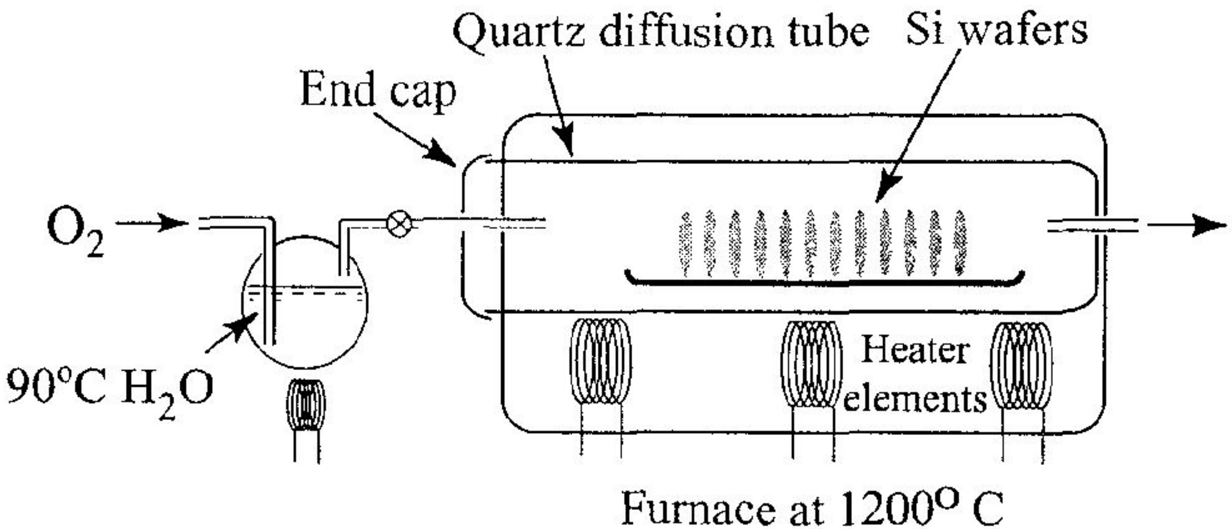
CVD

- Химическое осаждение из газовой фазы. Chemical vapor deposition
- Temperature > 300 °C.
- Growth rate from 5 to 100 nm/min.
- Materials:
  polysilicon (650-700°C),
  amorphous silicon (550-600 °C),
  SiO (силан + кислород, 300-900 °C),
  SiN (силан + аммиак, 700-900 °C),
  W, Ti, Tm, metal nitrides, Cu, dielectrics etc.
- Остаточные напряжения в поликремнии и других материалах требуют высокотемпературного отжига. Residual stress in polisilicon and other materials requires high-temperature anneal.



Термическое окисление. Thermal oxidation

- Атмосфера кислорода, oxygen flux, 850-1150 °C.
- Аморфный SiO_2, толщина зависит от температуры, давления, времени. Amorphous Si films with thickness depending on ambient temperature, pressure and process time.
- В пленках термического окисла образуются остаточные сжимающие напряжения. Thermal oxide possesses residual compressive stress.

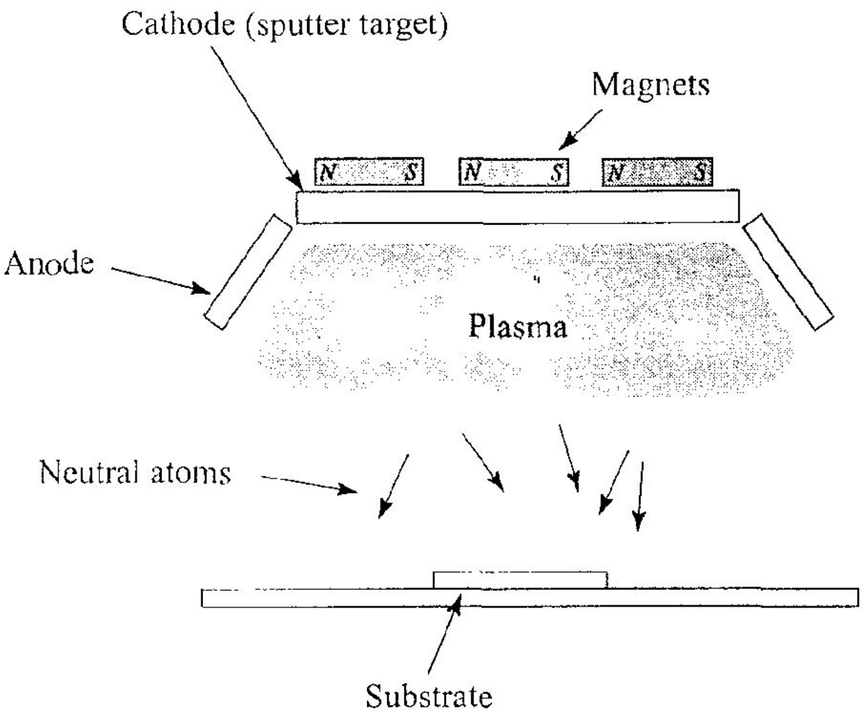


Apparatus for the wet oxidation of silicon. Dry oxides may be grown by bypassing the heated water bath.

Распыление Sputtering

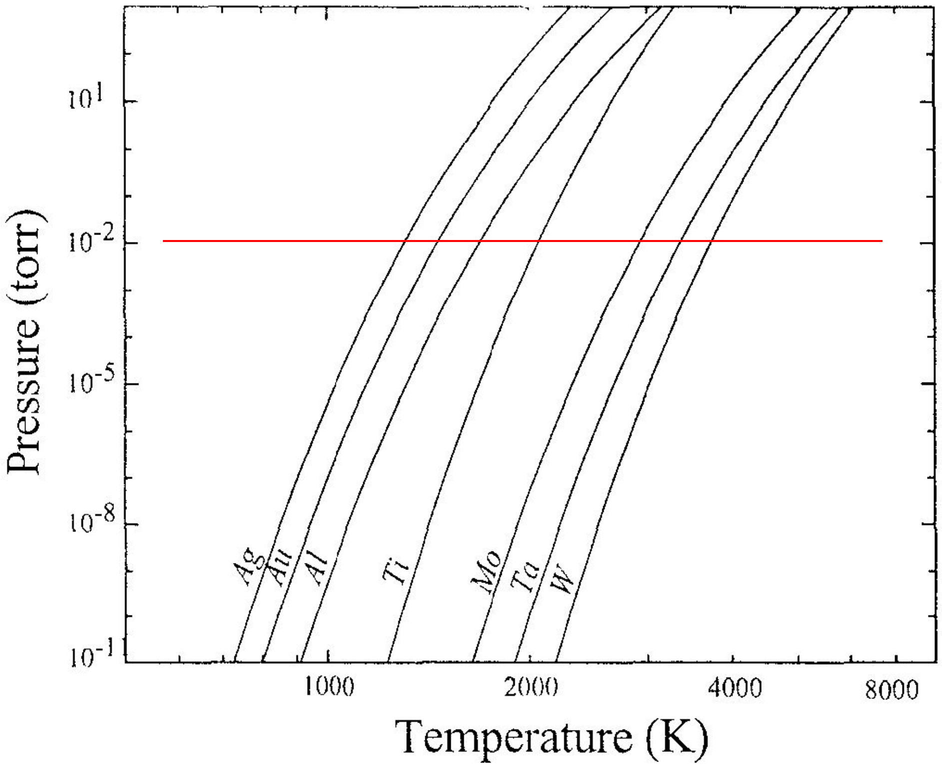
- Бомбардировка ионами, возможно в присутствии внешних полей: СВЧ, магнетронное, и др. Bombardment of target by ions, sometime in presence of external field, such as magnetic or UHF
- Распыляемая мишень осаждается на подложку в вакуумной камере. Sputtered target atoms deposit on a substrate.
- Типичная скорость напыления 0.1-0.3 мкм/мин. Deposition rate of 0.1-0.3 μm/min.
- Типичная температура < 150 °C. Deposition temperature < 150 °C.
- Materials: Al, Ti, Cr, Pt, Pl, W, Al/Si & Ti/W alloys, amorphous Si, dielectrics, including glasses and piezoceramics (PZT и ZnO).
- Реактивное распыление металлов с участием азота или кислорода приводит к образованию пленок таких соединений как TiN или TiO_2. Reactive sputtering of metals with N and O results in formation of thin film of TiN or TiO_2.

Схема установки магнетронного распыления Schematic setup



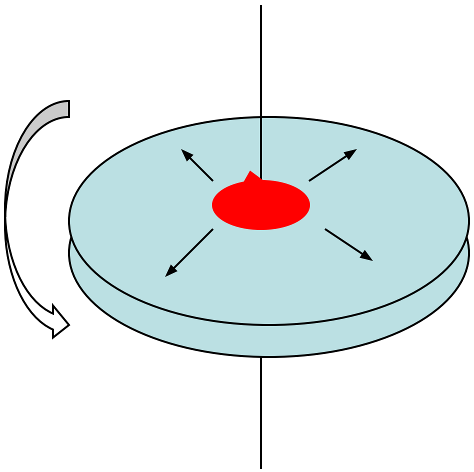
Испарение Evaporation

- Термическое, лазерное, электронное Thermal, laser, electron-beam heating
- Источник испаряется в вакуумной камере и осаждается на подложку. Evaporating source deposits on a substrate
- Скорость напыления 5-100 нм/мин. Deposition rate of 5-100 nm/min.
- Materials: Al, Si, Ti, Au, Cr, Mo, Ta, Pd, Pt, Ni/Cr, Al_2O_3, и пр.
- В пленках обычно есть сильные остаточные растягивающие напряжения. Films are residually stressed.



Spin-On Methods

- Жидкий раствор напыляется из сопла на середину пластины, которая раскручивается со скоростью от 500 до 5000 оборотов в минуту в течение 0.5-1 мин. для образования пленки постоянной толщины.
  Liquid solution drops in the middle of rotating plate. Rotation rate of 500 to 5000 per minute requires to produce a uniform film.
- Материалы: резисты, органические полимеры, стекла.
  Materials are resists, organic polymers, glasses.

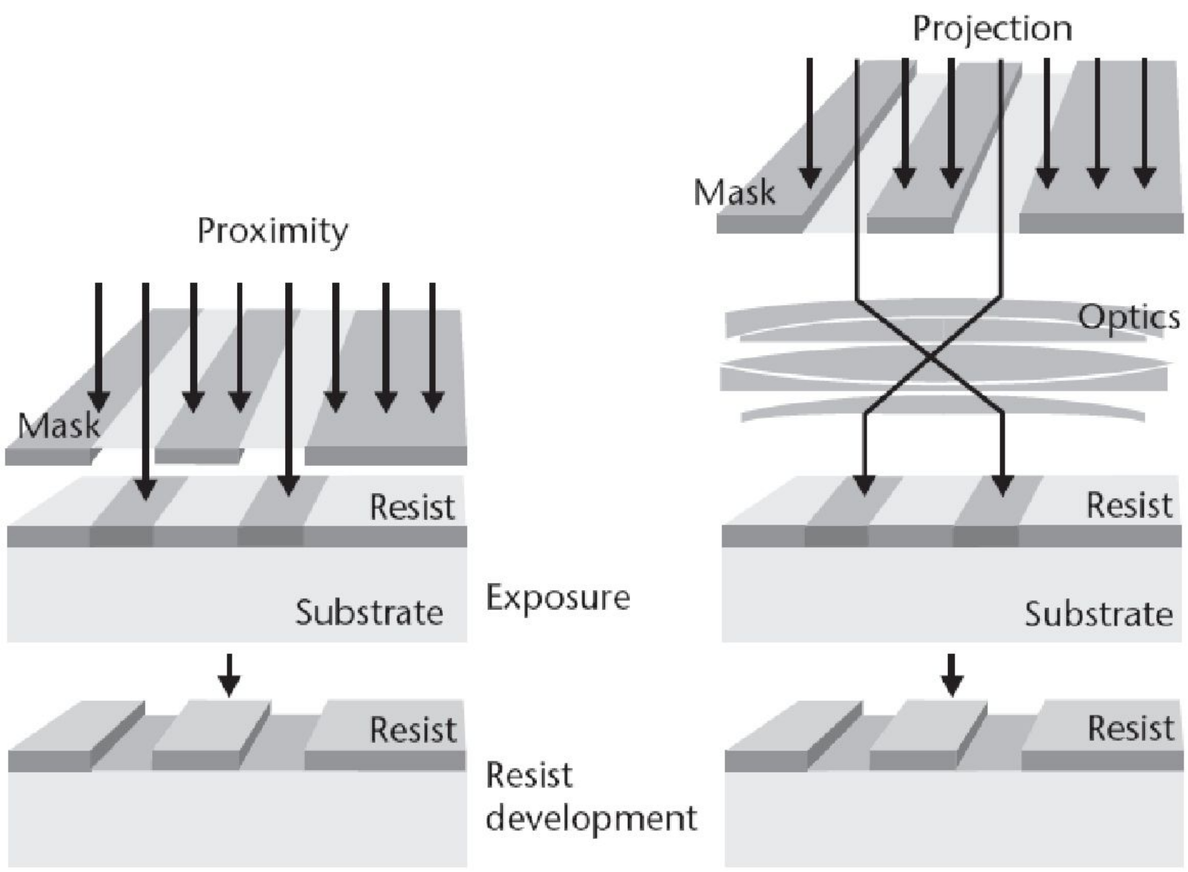


Литография Litography

- Нанесение резиста
  Deposition of resist.

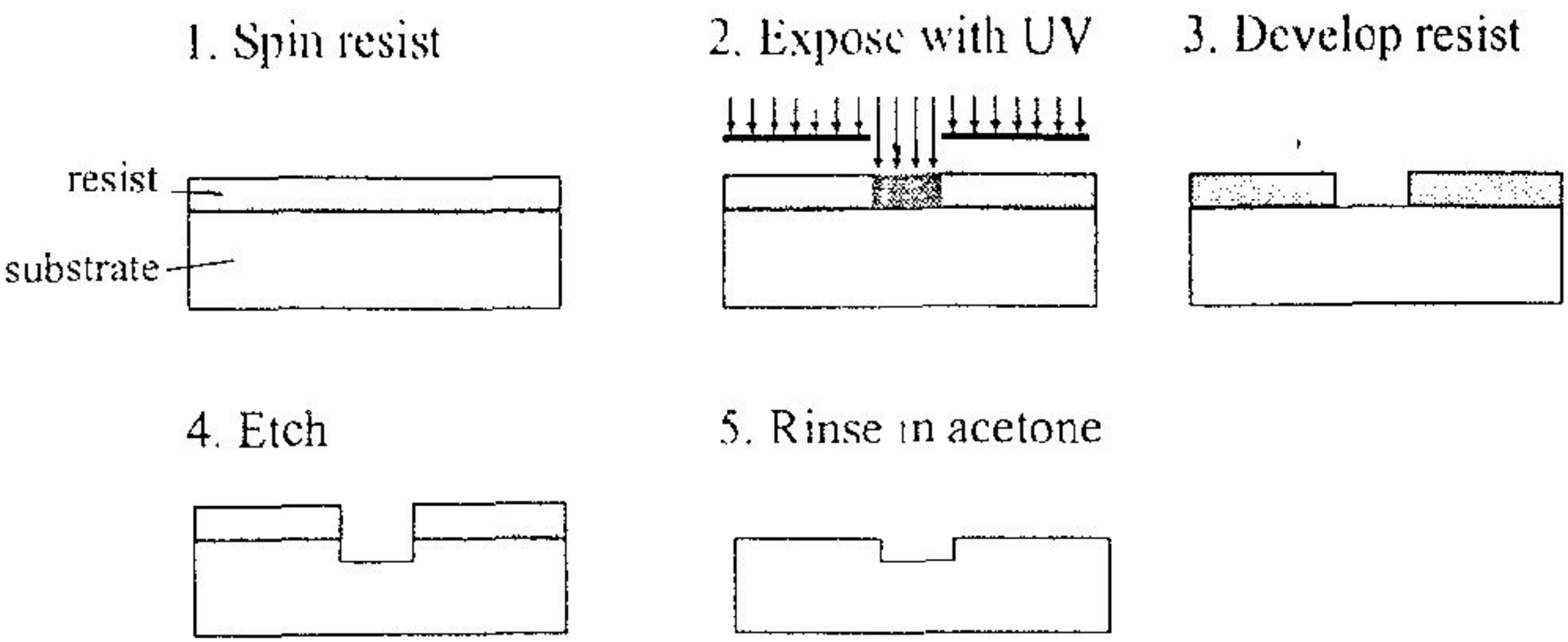
- Перенесение изображения маски на резист.
  Imaging mask on resist

- Селективное травление резиста и материала под ним.
  Selective etching of resist and underlying material.

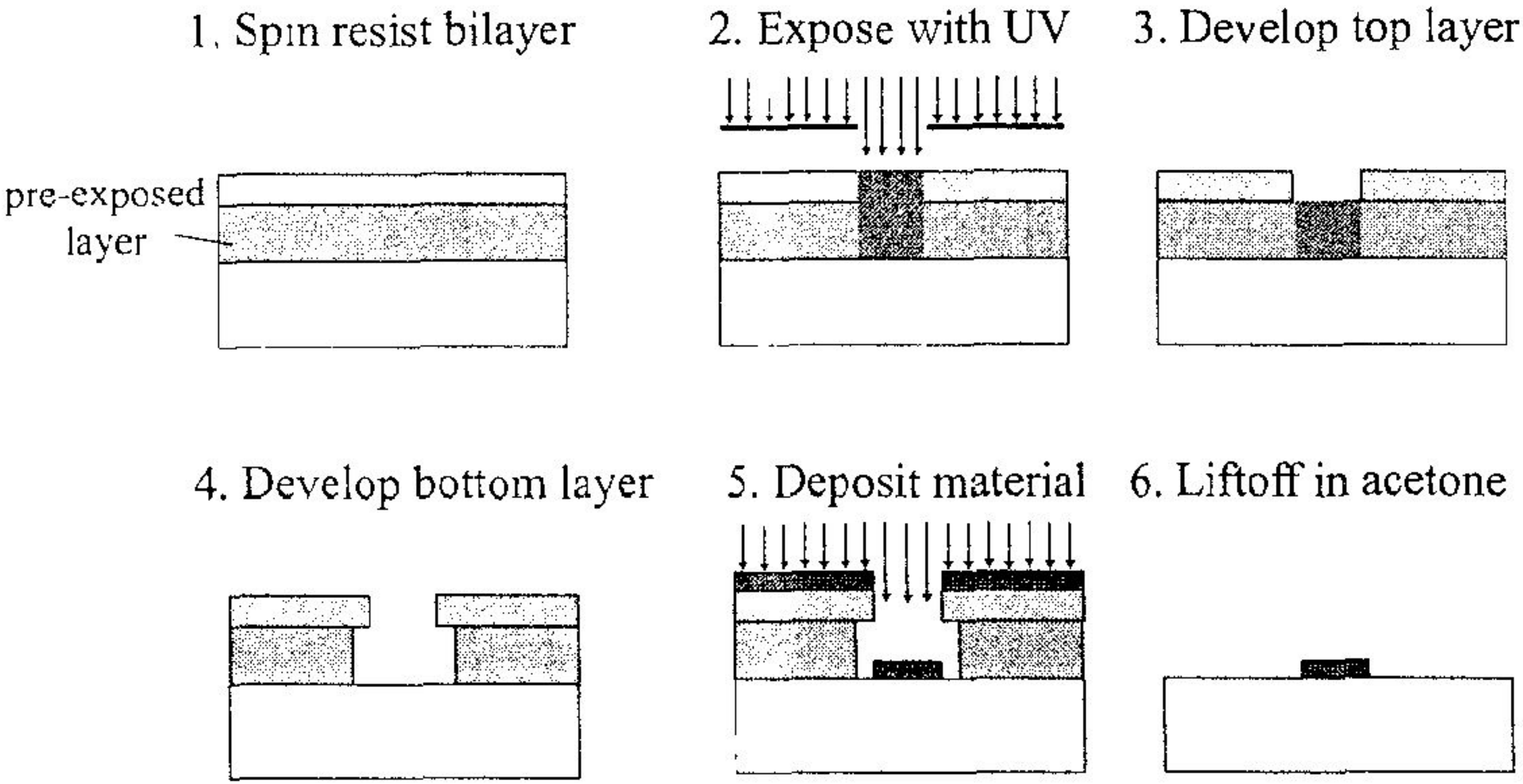


An illustration of proximity and projection lithography. In proximity mode, the mask is within 25 to 50 μm of the resist. Fresnel diffraction limits the resolution and minimum feature size to ~ 5 μm. In projection mode, complex optics image the mask onto the resist. The resolution is routinely better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

Фотолитография. Photolithography.



Lift-off метод



Пленка напыляется на профиль резиста. Резист удаляется вместе с нанесенной на него сверху пленкой.

Фотолитография. Photolithography.

- Проекционная фотолитография позволяет получить разрешение λ/2. Diffraction limit of resolution is λ/2.
- Используется УФ свет, UV light sources
  - 365 nm Hg лампа
  - 243 nm Kr-F лазер
  - 193 nm Ar-F лазер
- Рентгеновское синхротронное излучение позволяет получить разрешение 30 nm X-ray synchrotron source provides up to 30 nm

Использование ближнего поля для улучшения разрешения
Near-field techniques to improve resolution

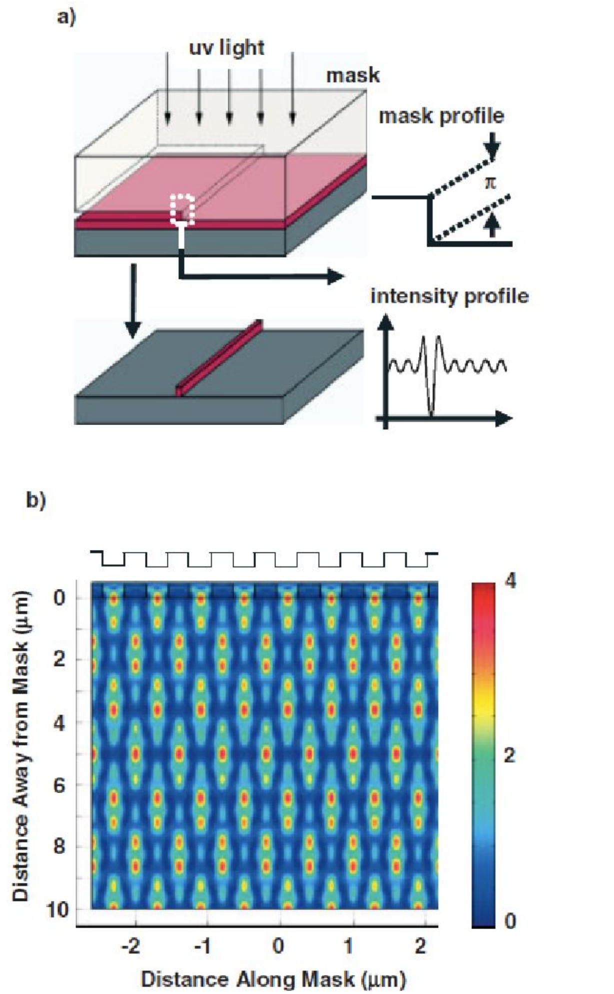
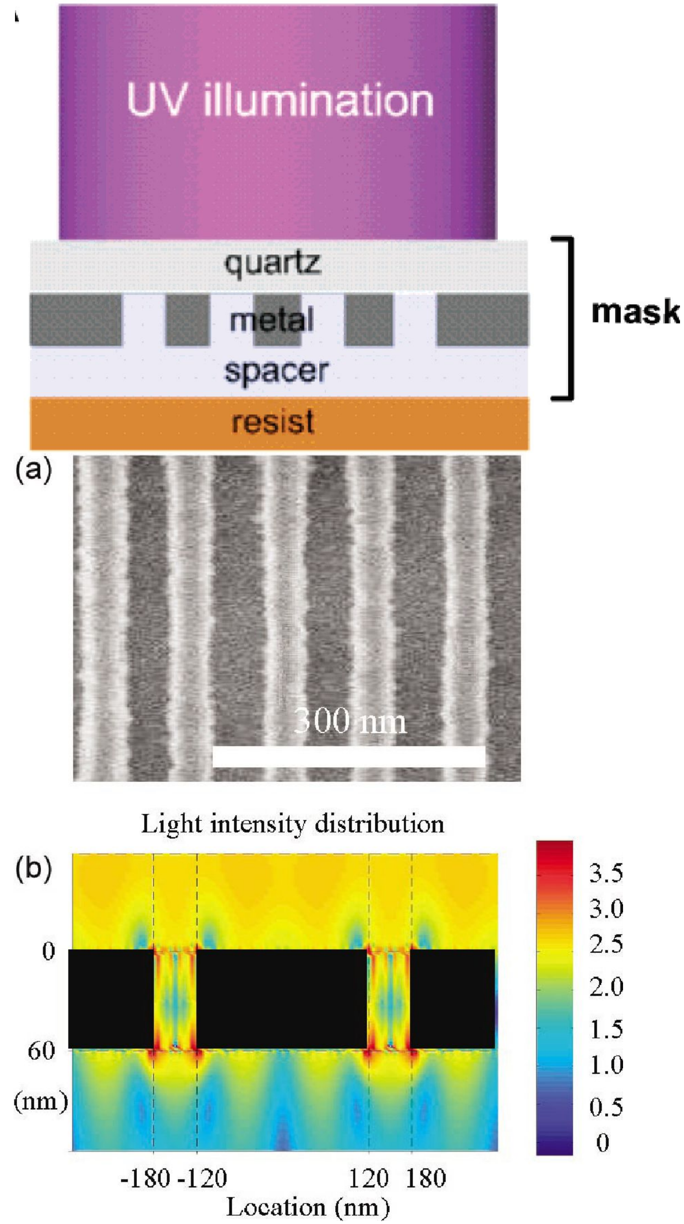
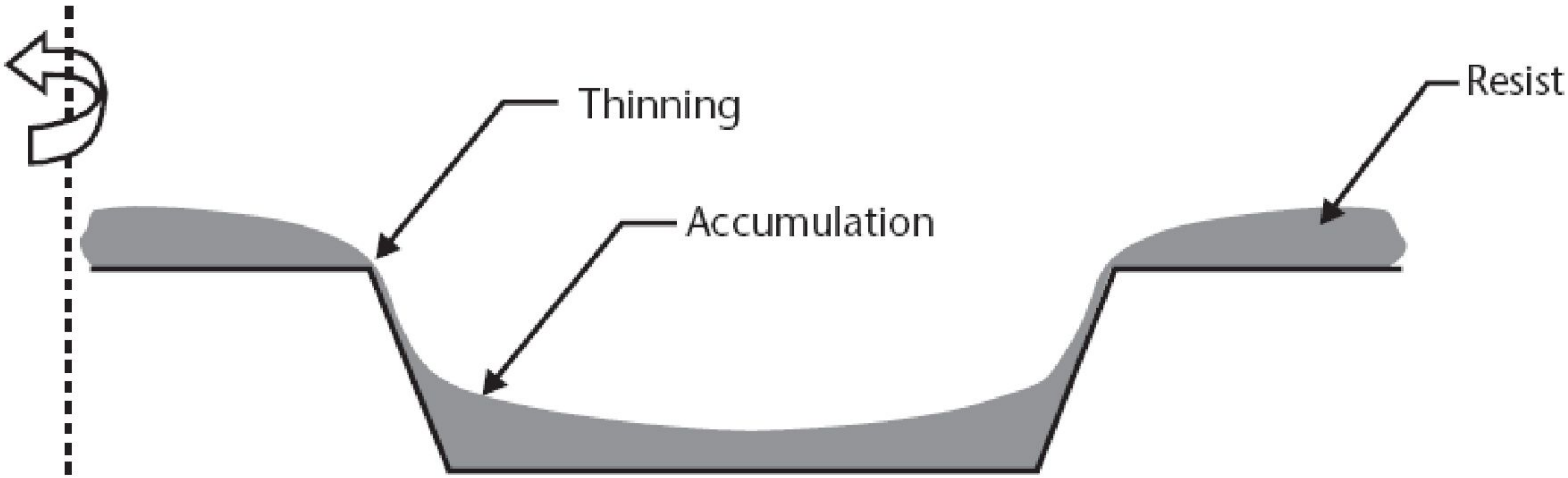


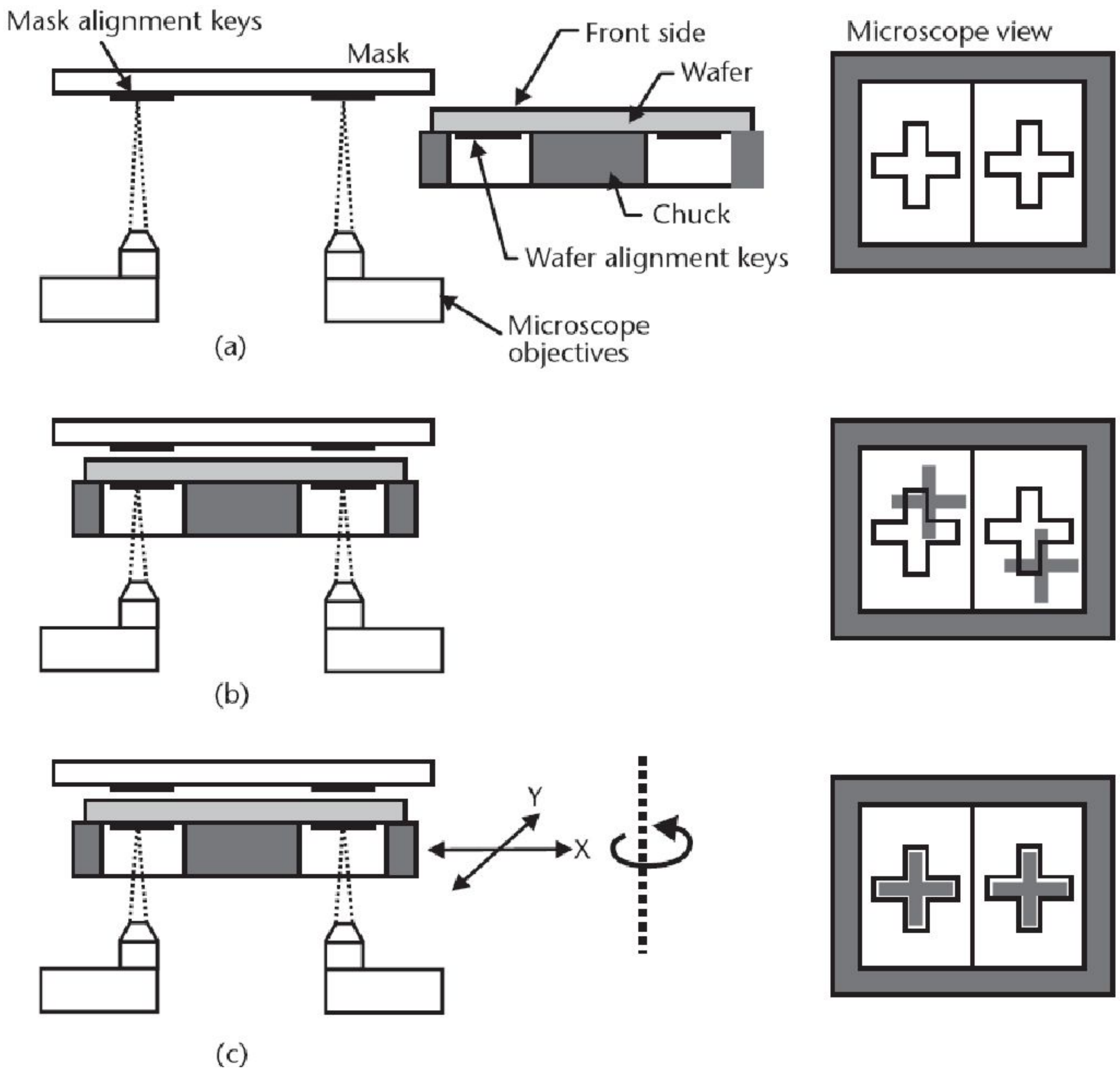
Figure 3. a) A schematic illustration of near-field exposure of a thin layer of positive resist with a conformable phase mask. A step edge of relief with a depth suitable for modulating the optical phase by π leads to a phase shadow with a characteristic width of ~100 nm for 365 nm exposure light. Developing the resist yields a line with a similar width. b) Finite-element modeling of the passage of a plane wave through a mask that presents relief features with widths comparable to the optical wavelength. This distribution of intensity can be used for fabricating 3D nanostructures in thick, transparent layers of photopolymers.



Нанесение резиста и литография для поверхности с глубоким профилем
Deposition of resist on a surface with deep profile



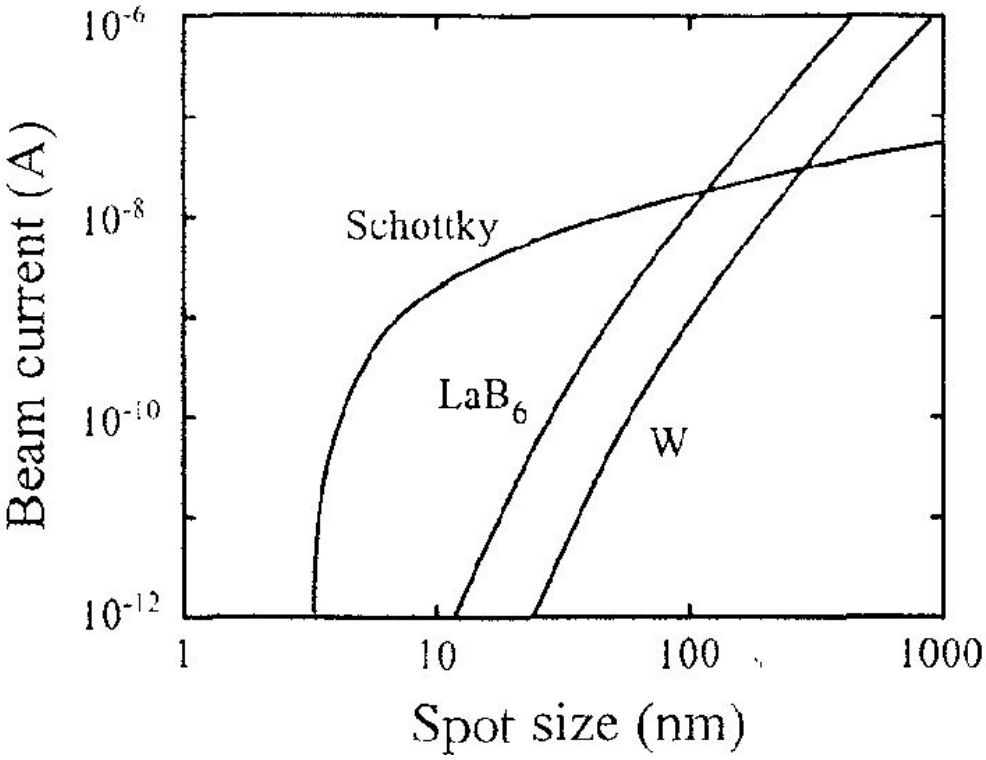
Двусторонняя литография. Double side lithography.



Double-sided alignment scheme for the SUSS MA-6 alignment system: (a) the image of mask alignment marks is electronically stored; (b) the alignment marks on the back side of the wafer are brought in focus; and (c) the position of the wafer is adjusted by translation and rotation to align the marks to the stored image. The right-hand side illustrates the view on the computer screen as the targets are brought into alignment.

Литография с помощью электронных пучков
Electron beam lithography

- Холодная полевая эмиссия электронов Шоттки. Cold field emission.
- Термоионная эмиссия электронов (2000-2500 К) Thermo-ionic emission
  - Вольфрам W (долговечный источник) (durable source)
  - Гексаборид лантана LaB_6 (яркий источник) (bright source)



Электронный пучок ускоряется напряжением 100 – 200 кВ
Electron beam is accelerated by 100-200 kV voltage

Литография реализуется как процесс движения пучка:
- не требуется маска (no mask required)
- производительность ограничена (limited writing rate)

Можно получить разрешение лучше 10 нм
Achievable resolution is better than 10 nm

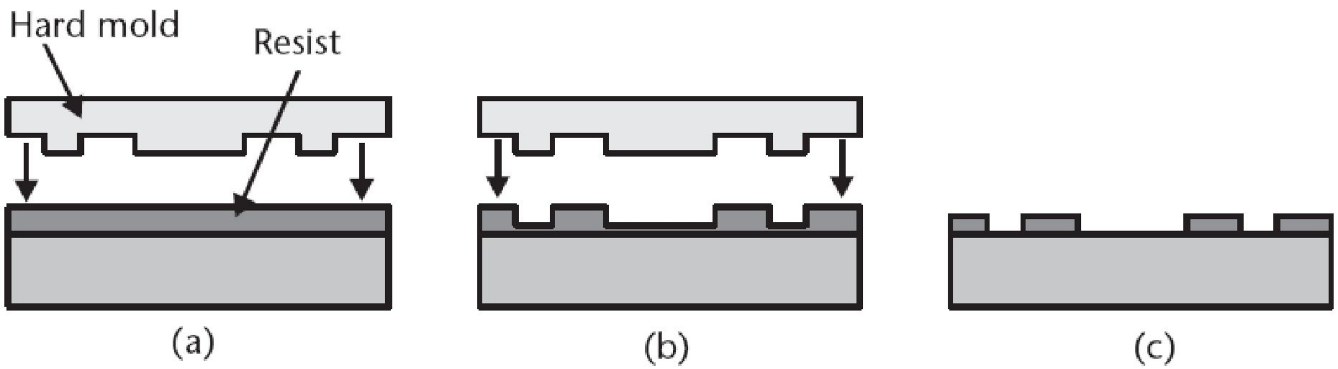
Сфокусированные ионные пучки
Focused ion beams

- Альтернатива электронной литографии
  Alternative to electron beam lithography
- Нет маски No mask
- Можно получить разрешение лучше 10 нм
  Resolution is bettter than 10 nm
- Ионы (Ions)
  – легкоплавкие металлы Ga, Bi, Hg
  – инертные газы Ar, He, Xe

Scanned-Probe Lithography

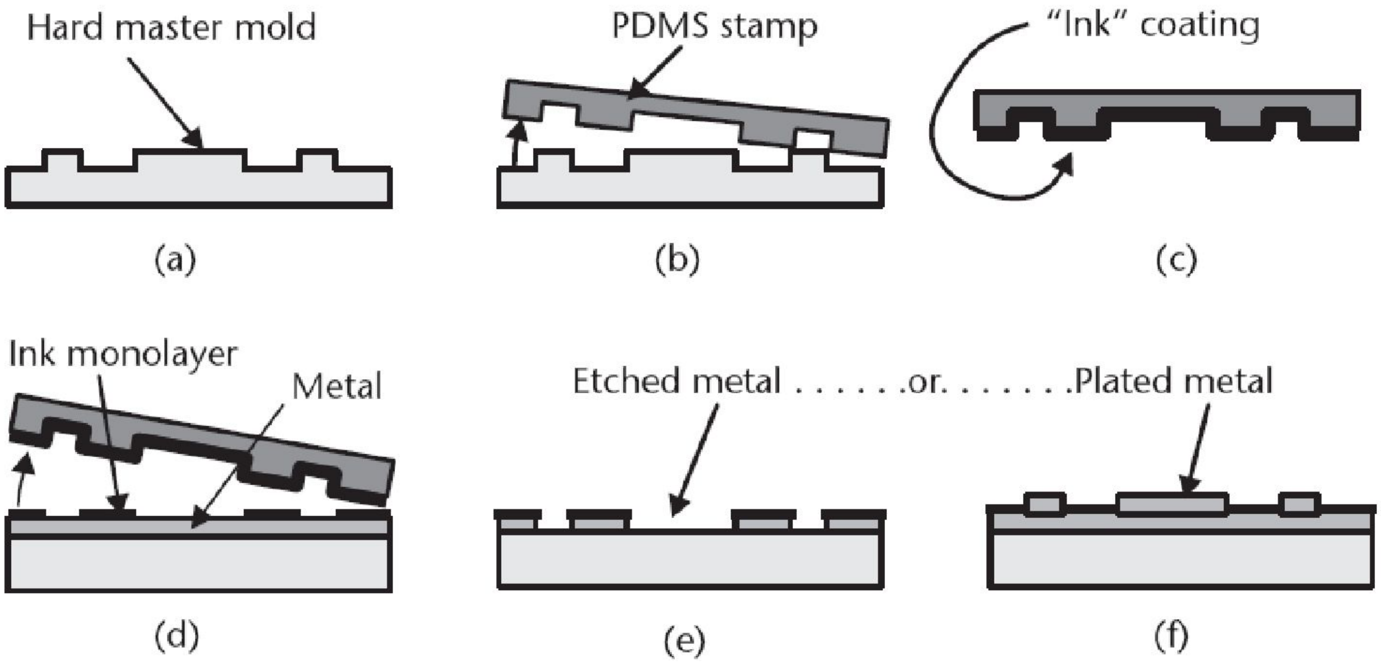
- AFM and STM
- Resolution 1-100 nm
- No mask
- Limited writing rate

Наноштамповка Nanoimprint



Nanoimprint lithography: (a) press hard mold into resist coating; (b) remove mold; and (c) RIE to remove residue

Штамповка литографической маски



Microcontact printing: (a) create master; (b) form PDMS stamp and peel off; (c) coat with "ink"; (d) press inked stamp against metal and remove, leaving ink monolayer; (e) use selfassembled monolayer as an etch mask; or (f) as a plating mask.

Заключение Conclusion

- Базовым материалом НЭМС является кремний
  Si is the material of choice for majority of NEMS
- Последовательные циклы напыление-литография-травление позволяет получать структуры со сложным пространственным профилем
  Consequent cycles of deposition-lithography-etching allow one to produce structures with complicated 3D profile

To be continued