

Material Aspects of Micro- and Nanoelectromechanical Systems

Springer Handbook of Nanotechnology,
Bharat *Bhushan* Editor

Springer-Verlag Berlin Heidelberg 2004 Printed in Germany



**An Introduction to
Microelectromechanical
Systems Engineering**

Second Edition

**Nadim Maluf
Kirt Williams**

- Two of the more significant technological achievements during the last 30 years have been the development of MEMS and its new offshoot, NEMS.
- These developments were made possible by significant advancements in the materials and processes used in the fabrication of MEMS and NEMS devices.
- And while initial developments capitalized on a mature Si infrastructure, recent advances have used materials and processes not associated with IC fabrication, a trend that is likely to continue as new application areas are identified.

- A well-rounded understanding of MEMS and NEMS requires a basic knowledge of the materials used to construct the devices, since material properties often govern device performance.
- Devices are rarely constructed of a single material, but rather a collection of materials, each providing a critical function and often working in conjunction with each other.
- A preview of the materials selected for inclusion is presented in Table 7.1. From this table it is easy to see that this chapter is not a summary of all materials used in MEMS and NEMS.

Table 7.1 Distinguishing characteristics and application examples of selected materials for MEMS and NEMS

Material	Distinguishing Characteristics	Application Examples
Single crystal Silicon (Si)	High quality electronic material, selective anisotropic etching	Bulk micromachining, piezoresistive sensing
Polycrystalline Si (polysilicon)	Doped Si films on sacrificial layers	Surface micromachining, electrostatic actuation
Silicon Dioxide (SiO ₂)	Insulating, etched by HF, compatible with polysilicon	Sacrificial layer in polysilicon surface micromachining, passivation layer for devices
Silicon Nitride (Si ₃ N ₄ , Si _x N _y)	Insulating, chemically resistant, mechanically durable	Isolation layer for electrostatic devices, membrane and bridge material
Polycrystalline Germanium (poly Ge), Polycrystalline Silicon-Germanium (poly Si-Ge)	Deposited at low temperatures	Integrated surface micromachined MEMS
Gold (Au), Aluminum (Al)	Conductive thin films, flexible deposition techniques	Innerconnect layers, masking layers, electromechanical switches
Nickel-Iron (NiFe)	Magnetic alloy	Magnetic actuation
Titanium-Nickel (TiNi)	Shape-memory alloy	Thermal actuation
Silicon Carbide (SiC) Diamond	Electrically and mechanically stable at high temperatures, chemically inert, high Young's modulus to density ratio	Harsh environment MEMS, high frequency MEMS/NEMS
Gallium Arsenide (GaAs), Indium Phosphide (InP), Indium Arsenide (InAs), and related materials	Wide bandgap, epitaxial growth on related ternary compounds	RF MEMS, optoelectronic devices, single crystal bulk and surface micromachining
Lead Zirconate Titanate (PZT)	Piezoelectric material	Mechanical sensors and actuators
Polyimide	Chemically resistant, high temperature polymer	Mechanically flexible MEMS, bioMEMS
SU-8	Thick, photo-definable resist	Micromolding, high-aspect-ratio structures
Parylene	Biocompatible polymer, deposited at room temperature by CVD	Protective coatings, molded polymer structures

Table 2.1 Properties of Selected Materials

<i>Property^a</i>	<i>Si</i>	<i>SiO₂</i>	<i>Si₃N₄</i>	<i>Quartz</i>	<i>SiC</i>	<i>Diamond</i>	<i>GaAs</i>	<i>AlN</i>	<i>92% Al₂O₃</i>	<i>Polyimide</i>	<i>PMMA</i>
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	2.5–40	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

^aProperties can vary with crystal direction, crystal structure, and grain size.

^bSublimates before melting.

^cGlass transition temperature given for polymers.

1. Single Crystal Silicon

- Single crystal Si is material for bulk and surface micromachining, due to the availability of anisotropic etching processes in conjunction with good mechanical properties.
- Having a Young's modulus of about **190 GPa**, Si compares favorably, from a mechanical perspective, with steel, which has a Young's modulus of about **210 GPa**.
- Favorable mechanical properties enable Si to be used as a material for membranes, beams, and other such structures.
- For surface micromachining applications, single crystal Si substrates are used primarily as mechanical platforms on which Si and non-Si device structures can be fabricated.
- Use of high-quality single crystal wafers enables the fabrication of integrated MEMS devices, at least for materials and processes that are compatible with Si ICs.

- Bulk micromachining is a process whereby etching techniques are used in conjunction with etch masks and etch stops to selectively sculpt micromechanical structures from a bulk substrate.
- From the materials perspective, single crystal Si is a relatively easy material to bulk micromachine, due to the availability of anisotropic etchants, such as **potassium hydroxide (KOH)** and **tetramethyl-aluminum hydroxide (TMAH)**, that attack the (100) and (110) Si crystal planes significantly faster than the (111) crystal planes.
- For example, the etching rate ratio of (100) to (111) planes in Si is about **400:1** for a typical **KOH/water** etch solution.
- Silicon dioxide (SiO_2), silicon nitride (Si_3N_4), and some metallic thin films (e.g., Cr, Au, etc.) provide good etch masks for most Si anisotropic etchants.

- In contrast to anisotropic etching, isotropic etching exhibits no selectivity to the various crystal planes.
- Isotropic etching of Si is commonly used for removal of work-damaged surfaces, creation of structures in single-crystal slices, and patterning single-crystal or polycrystalline films.
- The most commonly used isotropic Si etchants are mixtures of hydrofluoric (HF) and nitric (HNO_3) acid in water or acetic acid (CH_3COOH), with the etch rate dependent on the ratio of HF to HNO_3 .
- In terms of etch stops, boron-doped Si is effective for some liquid reagents.

- Boron-doped etch stops are often less than 10 μ m thick, since the boron concentration in Si must exceed $7 \cdot 10^{19} \text{ cm}^{-3}$ for the etch stop to be effective, and the doping is done by diffusion.
- It is possible to create a boron-doped etch stop below an undoped Si layer using ion implantation; however, the practical implant depth is limited to a few microns.

- Dry etching processes are available to pattern single crystal Si. The process spectrum ranges from **physical** mechanisms such as **sputtering and ion milling** to **chemical** mechanisms such as **plasma etching**.
- Reactive ion etching (RIE) is used dry etching technique to etch Si. By combining both physical and chemical processes, RIE is a highly effective anisotropic Si etching technique that is **independent** of crystalline orientation.
- Fluorinated compounds such as **CF₄**, **SF₆**, and **NF₃**, or chlorinated compounds such as **CCl₄** or **Cl₂**, sometimes mixed with **He**, **O₂**, or **H₂**, are commonly used in Si RIE.

- The RIE process is **highly directional**, which enables direct pattern transfer from an overlying masking material to the etched Si surface.
- SiO₂ thin films are often used as a masking material, owing to its chemical durability and ease in patterning.
- Process limitations (i. e., etch rates) restrict the etch depths of Si **RIE** to **less than 10 microns**.
- However, a process called deep reactive ion etching (**DRIE**) has extended the use of anisotropic dry etching to depths **well beyond several hundred microns**.

- A wide variety of microfabricated devices have been made from single crystal Si, such as piezoresistive pressure sensors, accelerometers, and mechanical resonators, e.t.c.
- Using nearly the same approaches but on a smaller scale, top-down nanomachining techniques have been used to fabricate nanoelectromechanical devices from single crystal Si.
- Single crystal Si is particularly well-suited for nanofabrication, because high crystal quality substrates with very smooth surfaces are readily available.

- By coupling electron-beam (e-beam) lithography with conventional Si etching, device structures with submicron dimensions have been fabricated.
- Submicron, single crystal Si nanomechanical structures have been successfully micromachined from bulk Si wafers and silicon-on-insulator (SOI) wafers.
- An isotropic Si etch was performed to release the device structures, whereas in the **latter** (недавний), the 50 nm to 200 nm structures were released by dissolving the underlying oxide layer in HF.
- An example of nanoelectromechanical beam structures fabricated from a single crystal Si substrate is shown in Fig. 7.1.

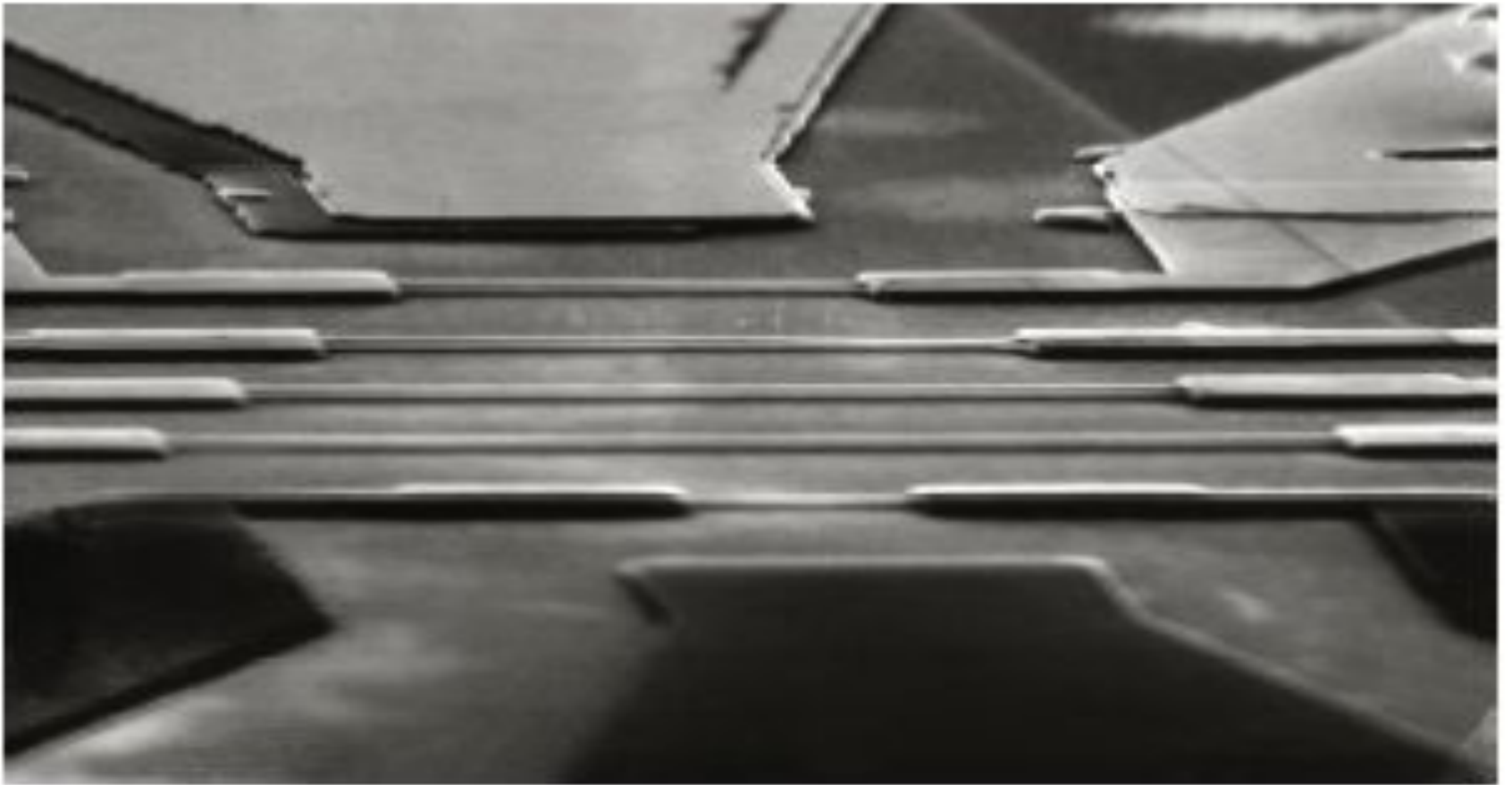


Fig. 7.1 A collection of Si nanoelectromechanical beam resonators fabricated from a single-crystal Si substrate (courtesy M. Roukes, Caltech)

In-plane nanoelectromechanical resonators based on silicon nanowire piezoresistive detection

- **E Mile*, G Jourdan*, I Bargatin *+1, S Labarthe *, C Marcoux *, P Andreucci *, S Hentz*, C Kharrat*, E Colinet*, and L Duraffourg***
- ***CEA/LETI MINATEC 17 rue des Martyrs. 38054 GRENOBLE CEDEX 9.**
- **+Condensed Matter Physics 114-36, California Institute of Technology, Pasadena, California 91125**

In-plane nanoelectromechanical resonators based on silicon nanowire piezoresistive detection

- The NEMS device presented in this paper is fabricated using CMOS compatible materials with nano-electronics state-of-the-art lithography and etching techniques.
- We used a 200-mm silicon-on-insulator (SOI) wafer of (100) orientation with a 160-nm-thick top silicon structural layer (resistivity $\approx 10 \Omega \cdot \text{cm}$) and a 400-nm-thick sacrificial oxide layer.

- The top silicon layer was implanted with boron ions (p-type) through a thin layer of thermal oxide.
- Homogenous doping ($\sim 10^{19} \text{cm}^{-3}$) in the whole thickness of the top silicon was obtained through specific annealing step (for material reconstruction and doping activation commonly used in CMOS technology), resulting in top layer resistivity of approximately $9 \text{ m}\Omega \cdot \text{cm}$.

- A hybrid e-beam/DUV lithography technique (allowing 50 nm minimum feature size) was used to define the nano-resonators and electrode pads, respectively.
- Top silicon layer was etched by anisotropic reactive ion etching (RIE). In order to decrease the **lead resistances** (**сопротивление выводов**), the interconnecting leads have been made thicker with a 650 nm thick AlSi layer, a typical metal for CMOS interconnections process.
- Finally, the nanoresonators have been released using a vapor HF isotropic etching to remove the sacrificial layer oxide beneath the structures.
- 1500 devices per wafer of such design are fabricated with this VLSI process. Functionality of the final devices is checked measuring both the lead and gauges resistances and resonant frequency. The yield is 95% per wafer in average.

- The NEMS is composed of a fixed-free lever beam and two piezoresistive gauges connected to the cantilever at a distance $l/1=0.15l$ from its fixed end where l is the beam length (see TAB. 1).
- This value was chosen to maximize the stress inside the gauges due to the cantilever motion (see FIG. 1).
- The gauges have been etched along the $\langle 110 \rangle$ direction in order to benefit from the high gauge factor associated with p^{++} doped silicon.
- A drive electrode was patterned along one side of the vibrating beam for electrostatic actuation.
- The general architecture is given in FIG. 1 and the device dimensions are summed up in TAB. 1.

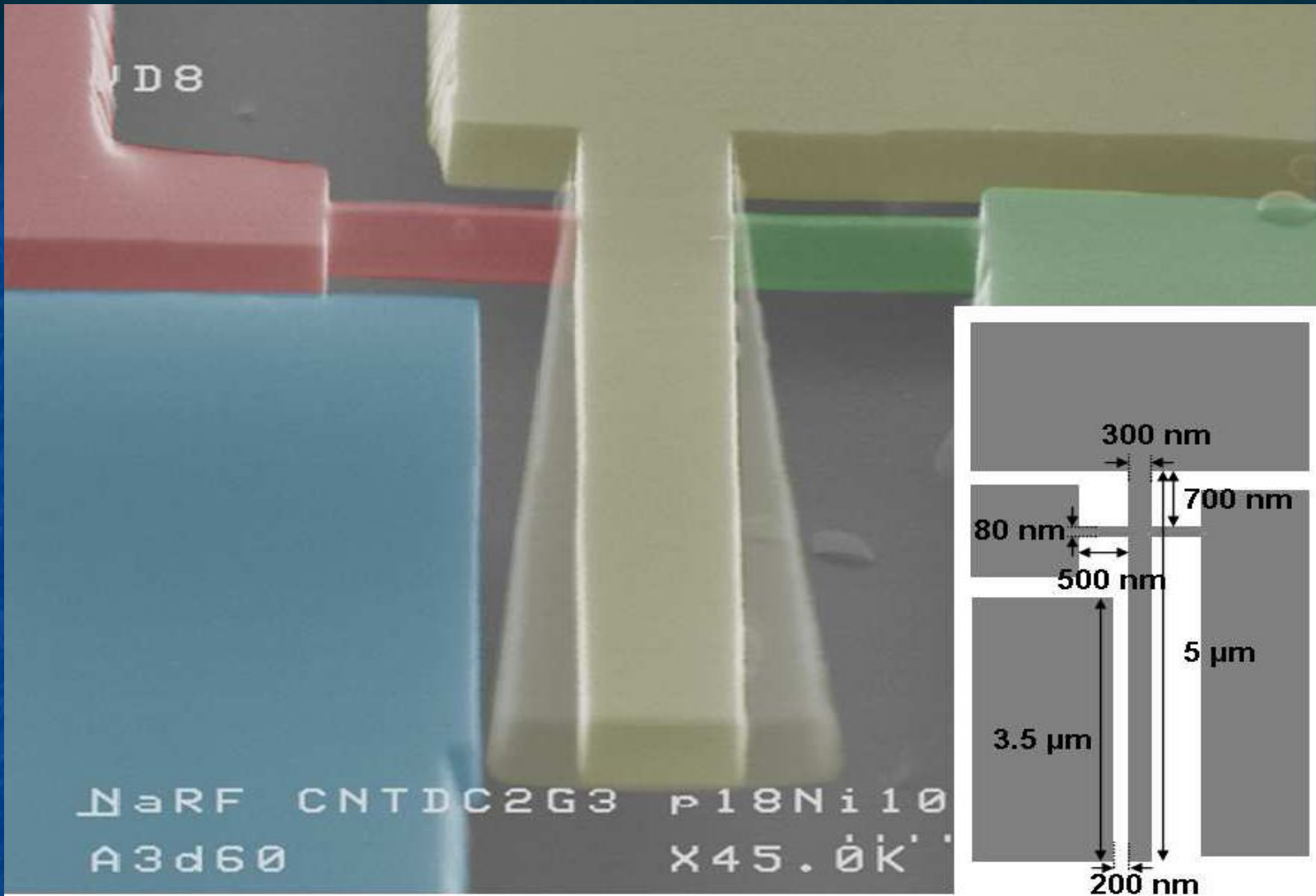
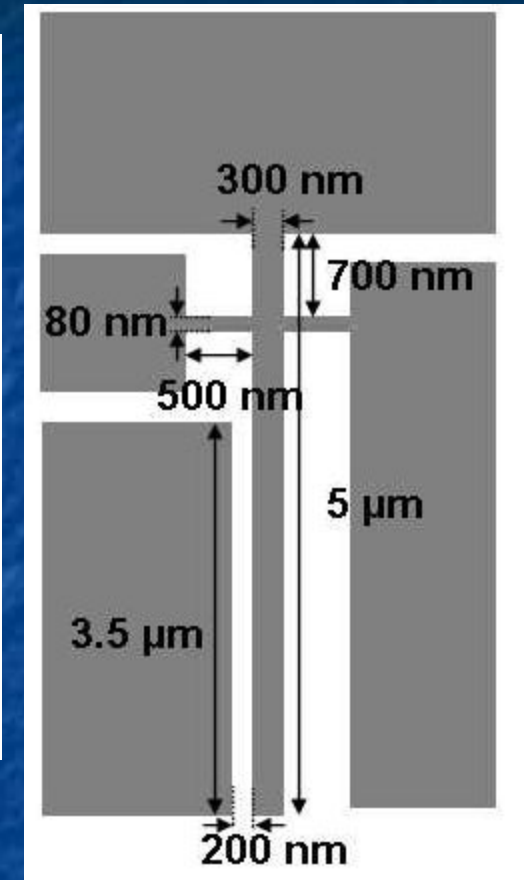


FIG.1 – Artificially colored and modified SEM image illustrating the in-plane vibration of the beam

TAB. 1 – Typical values of the device

Beam length l	Beam width w	Distance Anchor/Gauges l_1	Gauge length b	Gauge width w_1	Electrode length a	Gap Electrode/Beam g
$5\mu\text{m}$	300nm	700nm	500nm	80 nm	$3.5\mu\text{m}$	200nm

The lead resistance of approximately $4\text{ k}\Omega$ and the gauge resistance of $3.6\text{ k}\Omega$ were measured using the 3-point local AFM technique [15].



- Silicon as an element exists with three different microstructures: *crystalline*, *polycrystalline*, or *amorphous*.
- Polycrystalline, or simply “**polysilicon**,” and amorphous silicon are usually deposited as thin films with typical **thicknesses below 5 μm** .
- Crystalline silicon substrates are commercially available as circular wafers with **100-mm** (4-in) and **150-mm** (6-in) diameters. Larger-diameter (200-mm and 300-mm) wafers, used by the integrated circuit industry, are currently economically unjustified for MEMS.

■ .

- Standard 100-mm wafers are nominally 525 μm thick, and 150-mm wafers are typically 650 μm thick.
- Double-side-polished wafers commonly used for micromachining on both sides of the wafer are approximately 100 μm thinner than standard thickness substrates.
- The relatively low cost of these substrates (approximately \$10 for a 100-mm-diameter wafer and \$15 for a 150-mm wafer) makes them attractive for the fabrication of micromechanical components and systems

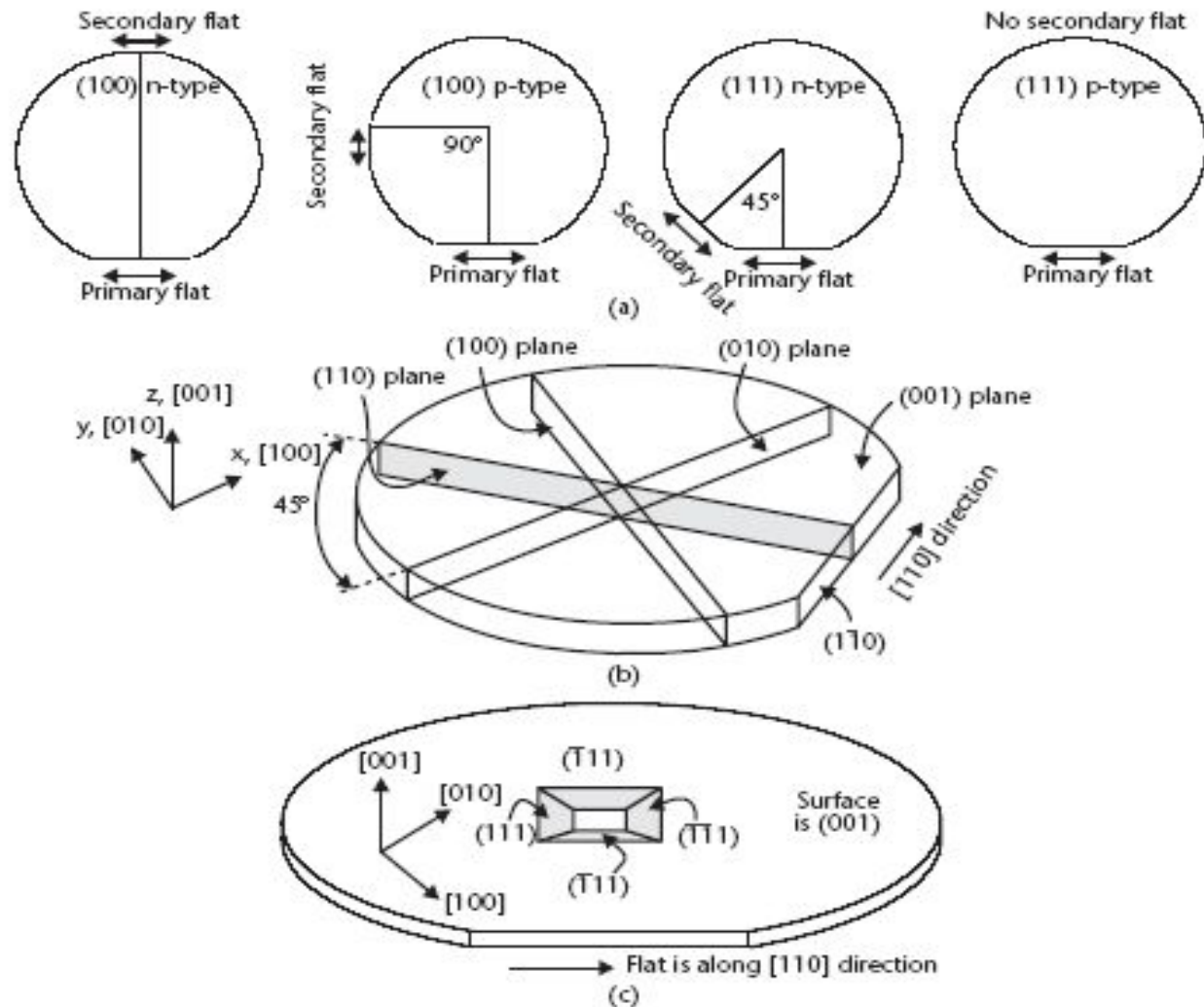


Figure 2.2 (a) Illustration showing the primary and secondary flats of {100} and {111} wafers for both *n*-type and *p*-type doping (SEMI standard); (b) illustration identifying various planes in a wafer of {100} orientation (the wafer thickness is exaggerated); and (c) perspective view of a {100} wafer and a KOH-etched pit bounded by {111} planes.

- 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 (поглотитель тепла).

- Unfortunately, silicon is not an active optical material—silicon-based lasers do not exist. Because of the particular interactions between the crystal atoms and the conduction electrons, silicon is effective only in detecting light; emission of light is very difficult to achieve.
- At infrared wavelengths above $1.1\ \mu\text{m}$, silicon is transparent, but at wavelengths shorter than $0.4\ \mu\text{m}$ (in the blue and ultraviolet portions of the spectrum), it reflects over 60% of the incident light (see Figure 2.3).
- The attenuation depth of light in silicon (the distance light travels before the intensity drops to 36% of its initial value) is $2.7\ \mu\text{m}$ at 633 nm (red) and $0.2\ \mu\text{m}$ at 436 nm (blue-violet). The slight attenuation of red light relative to other colors is what gives thin silicon membranes their translucent reddish tint (тонкие Si-мембраны имеют красноватый оттенок).

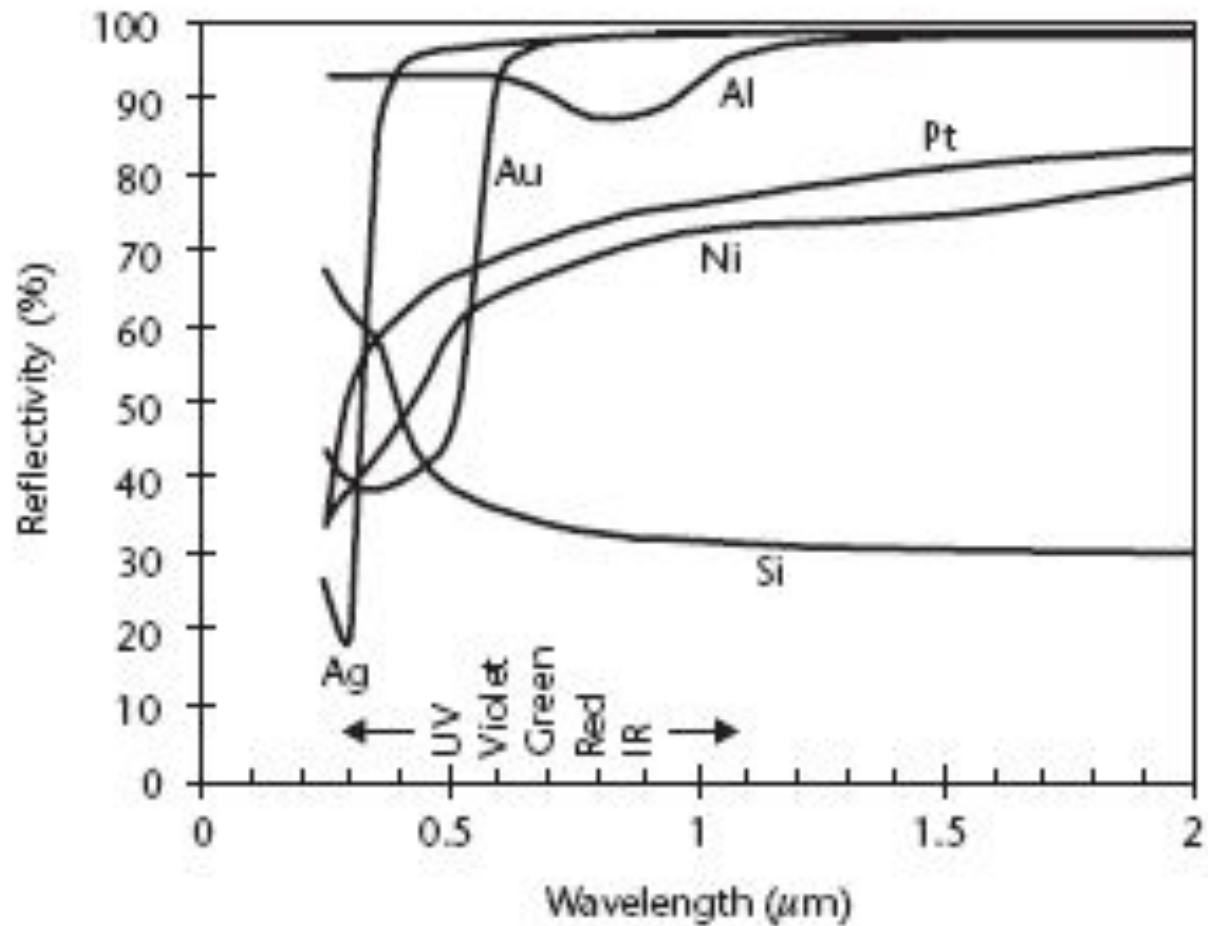


Figure 2.3 Optical reflectivity for silicon and selected metals.

- Silicon is also well known to retain its mechanical integrity at temperatures up to about **700°C** .
- At higher temperatures, silicon starts to soften and plastic deformation can occur under load.
- While the mechanical and thermal properties of polysilicon are similar to those of single crystal silicon, polysilicon experiences slow stress annealing effects at temperatures above **250°C**, making its operation at elevated temperatures subject to long-term instabilities, drift, and hysteresis effects.
- The surface of silicon oxidizes immediately upon exposure to the oxygen in air (referred to as *native oxide*).
- The oxide thickness self-limits at a **few nanometers** at room temperature. As silicon dioxide is very inert, it acts as a protective layer that prevents chemical reactions with the underlying silicon.

- The interactions of silicon with gases, chemicals, biological fluids, and **enzymes** (ферменты) remain the subject of many research studies, but, for the most part, silicon is considered stable and resistant to many elements and chemicals typical of daily applications.
- For example, experiments have shown that silicon remains **intact** (неповреждённый) in the presence of Freon™ gases as well as automotive fluids such as brake fluids (тормозная жидкость).
- Silicon has also proven to be a suitable material for applications such as **valves** for the delivery of **ultra-high-purity gases**.

- In medicine and biology, studies are ongoing to evaluate silicon for medical implants.
- Preliminary medical evidence indicates that silicon is benign (**доброкачественный**) in the body and does not release toxic substances when in contact with biological fluids; however, it appears from recent experiments that bare silicon surfaces may not be suitable for high-performance polymerase chain reactions (PCR) intended (**предназначенный**) for the amplification of genetic DNA material.
- The **polymerase chain reaction (PCR)** is a biochemical technology in **molecular biology** to **amplify** a single or a few copies of a piece of **DNA** across several orders of magnitude, generating

Table 2.2 Temperature Dependence of Some Material Properties of Crystalline Silicon

	300K	400K	500K	600K	700K
Coefficient of linear expansion (10^{-6} K^{-1})	2.616	3.253	3.614	3.842	4.016
Specific heat (J/g·K)	0.713	0.785	0.832	0.849	0.866
Thermal conductivity (W/cm·K)	1.56	1.05	0.8	0.64	0.52
Temperature coefficient of Young's modulus (10^{-6} K^{-1})	-90	-90	-90	-90	-90
Temperature coefficient of piezoresistance (10^{-6} K^{-1}) (doping $<10^{18} \text{ cm}^{-3}$)	-2,500	-2,500	-2,500	—	—
Temperature coefficient of permittivity (10^{-6} K^{-1})	1,000	—	—	—	—

(Source: [5].)

Polysilicon

- Surface micromachining is a process whereby a sequence of thin films, often of different materials, is deposited and selectively etched to form the desired micromechanical structure.
- In contrast to bulk micromachining, the substrate serves primarily as a platform to support the device.
- For Si-based surface micromachined MEMS, Si^* -polysilicon is most often used as the structural material, silicon dioxide (SiO_2) as the sacrificial material, silicon nitride (Si_3N_4) for electrical isolation of device structures, and single crystal Si as the substrate.

- Like single crystal Si, polysilicon can be doped during or after film deposition.
- SiO₂ can be thermally grown or deposited on Si over a broad temperature range (e.g., 200 °C to 1,150 °C) to meet various process and material requirements.

- SiO_2 is readily dissolvable in hydrofluoric acid (HF), which does not etch polysilicon and, thus, can be used to dissolve SiO_2 sacrificial layers.
- Si_3N_4 is an insulating film that is highly resistant to oxide etchants.
- The polysilicon micromotor shown in Fig. 7.2 was surface micromachined using a process that included these materials.

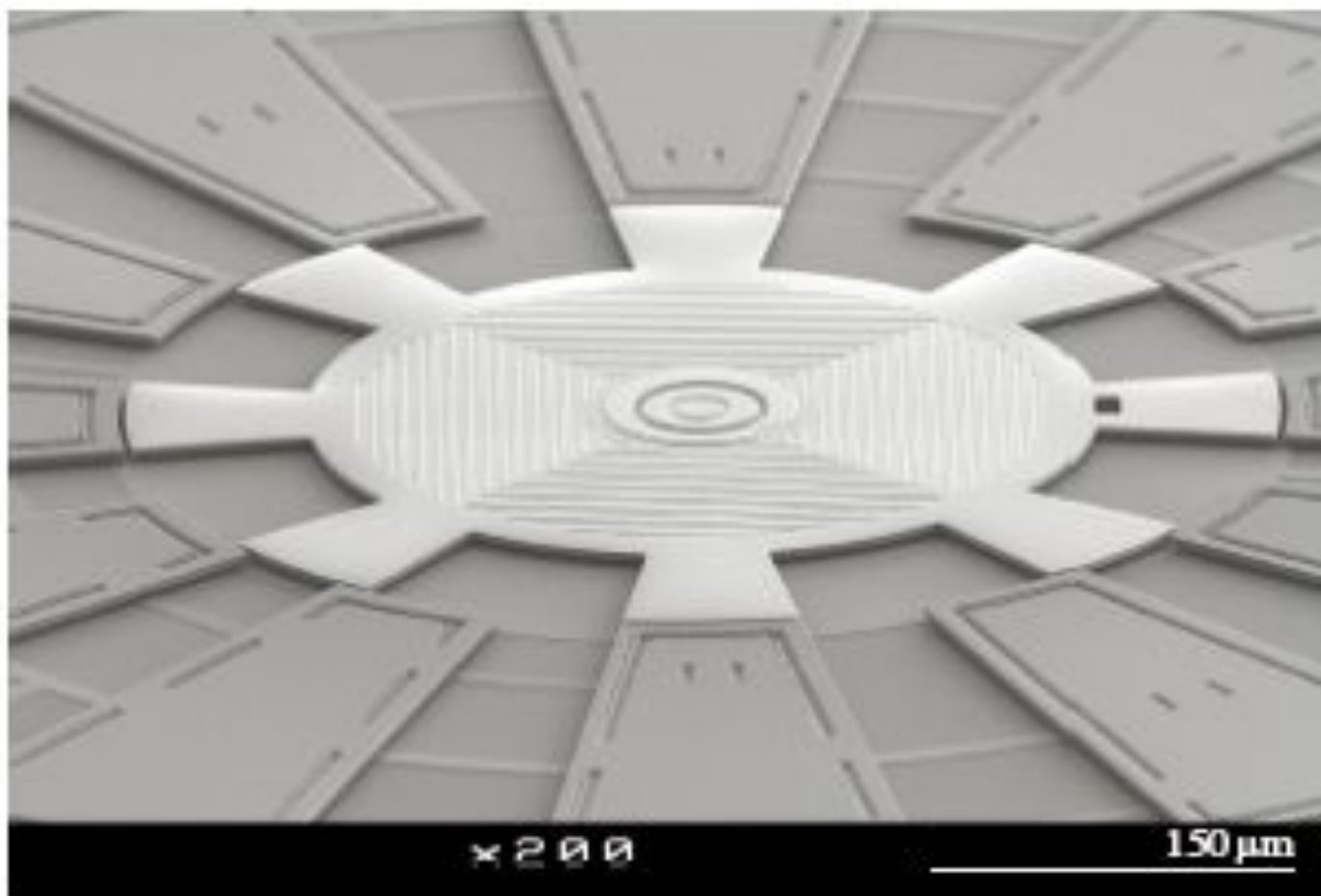
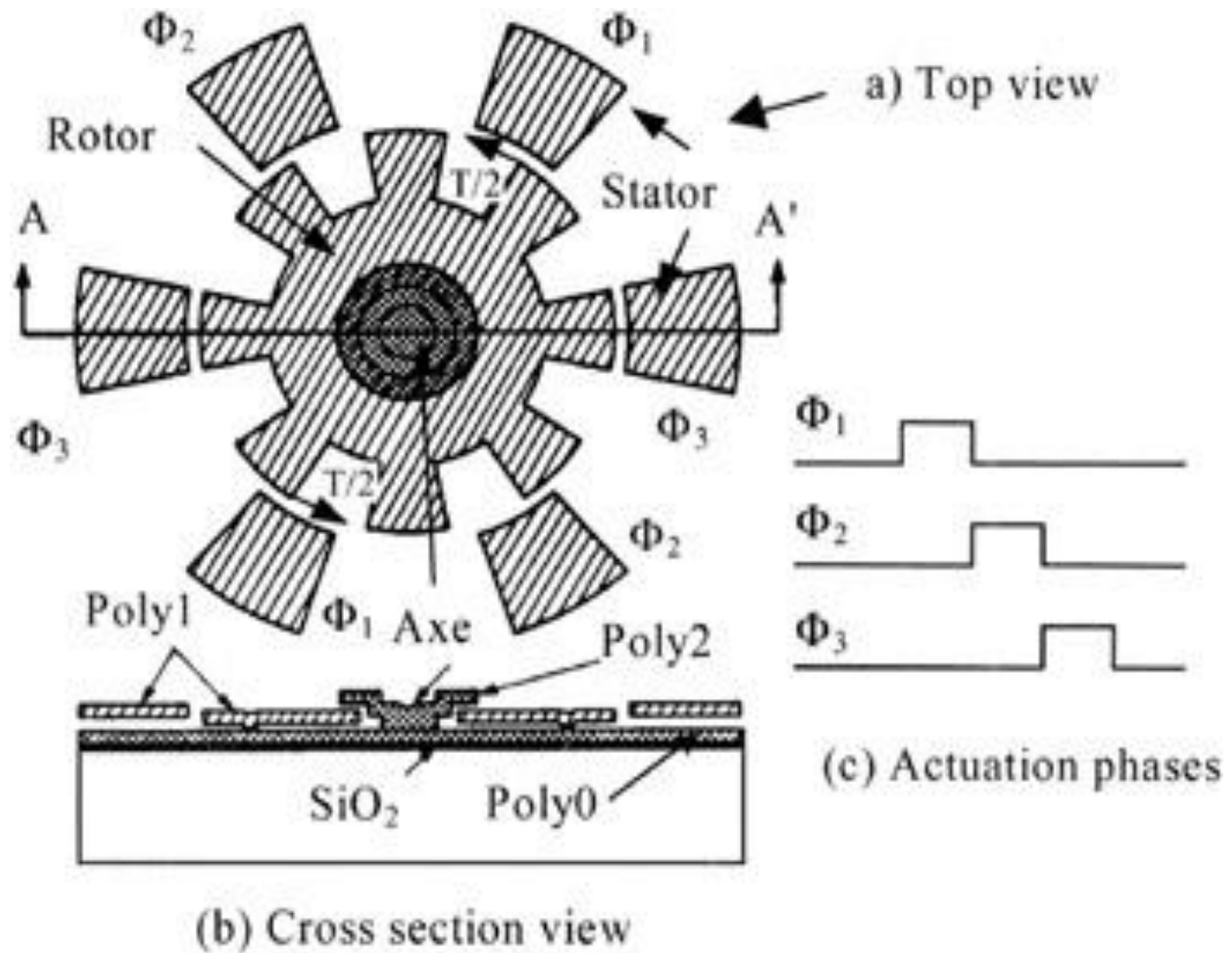


Fig. 7.2 SEM micrograph of a surface-micromachined polysilicon micromotor fabricated using a SiO_2 sacrificial layer



An **electrostatic motor** or **capacitor motor** is a type of [electric motor](#) based on the attraction and repulsion of [electric charge](#).

- For MEMS and IC applications, polysilicon films are commonly deposited using a process known as low-pressure chemical vapor deposition (LPCVD).
- The typical polysilicon LPCVD reactor is based on a hot wall, resistance-heated furnace.
- Typical processes are performed at temperatures ranging from 580 °C to 650 °C and pressures from 100 to 400 mtorr. The most commonly used source gas is silane (SiH_4).

- Polysilicon thin films consist of a collection of small single crystal grains whose microstructure and orientation is a function of the deposition conditions.
- For typical LPCVD processes (e.g., 200 mtorr), the amorphous-to-polycrystalline transition temperature is about 570 °C, with amorphous films deposited below the transition temperature.
- At 600 °C, the grains are small and equiaxed, while at 625 °C, the grains are large and columnar.
- The crystal orientation is predominantly (110) Si for temperatures between 600 °C and 650 °C, while the (100) orientation is dominant for temperatures between 650 °C and 700 °C.

- In terms of chemical resistance, polysilicon is very much like single crystal Si.
- The oxidation rate of undoped polysilicon is typically between that of (100)-and (111)-oriented single crystal Si.
- For temperatures **below 1,000 °C**, heavily phosphorus-doped polysilicon oxidizes at a rate significantly higher than undoped polysilicon.
- The resistivity of polysilicon can be modified using the doping methods developed for single crystal Si.

- Diffusion is an effective method for doping polysilicon films, especially for heavy doping of thick films.
- **Phosphorous**, which is the most commonly used dopant in polysilicon MEMS, diffuses significantly faster in polysilicon than in single crystal Si, **due primarily to enhanced diffusion rates along grain boundaries**.
- The diffusivity in polysilicon thin films (i. e., small equiaxed grains) is about $1 \cdot 10^{-12}$ cm²/s.

- Ion implantation is also used to dope polysilicon films.
- A high-temperature annealing step is usually required to electrically activate the implanted dopants, as well as to repair implant-related damage in the polysilicon films.
- In general, the conductivity of implanted polysilicon films is not as high as films doped by diffusion.
- **In situ** doping of polysilicon is performed by simply including a dopant gas, usually diborane (B_2H_6) or phosphine (PH_3), in the CVD process.

- The addition of dopants during the deposition process not only modifies the conductivity, but also affects the deposition rate of the polysilicon films.
- As shown in Fig. 7.3, the inclusion of boron generally **increases the deposition rate** of polysilicon relative to undoped films, while **phosphorus** (not shown) **reduces the rate**.
- **In situ** doping can be used to produce conductive films with uniform doping profiles without requiring the high-temperature steps usually associated with diffusion or ion implantation.

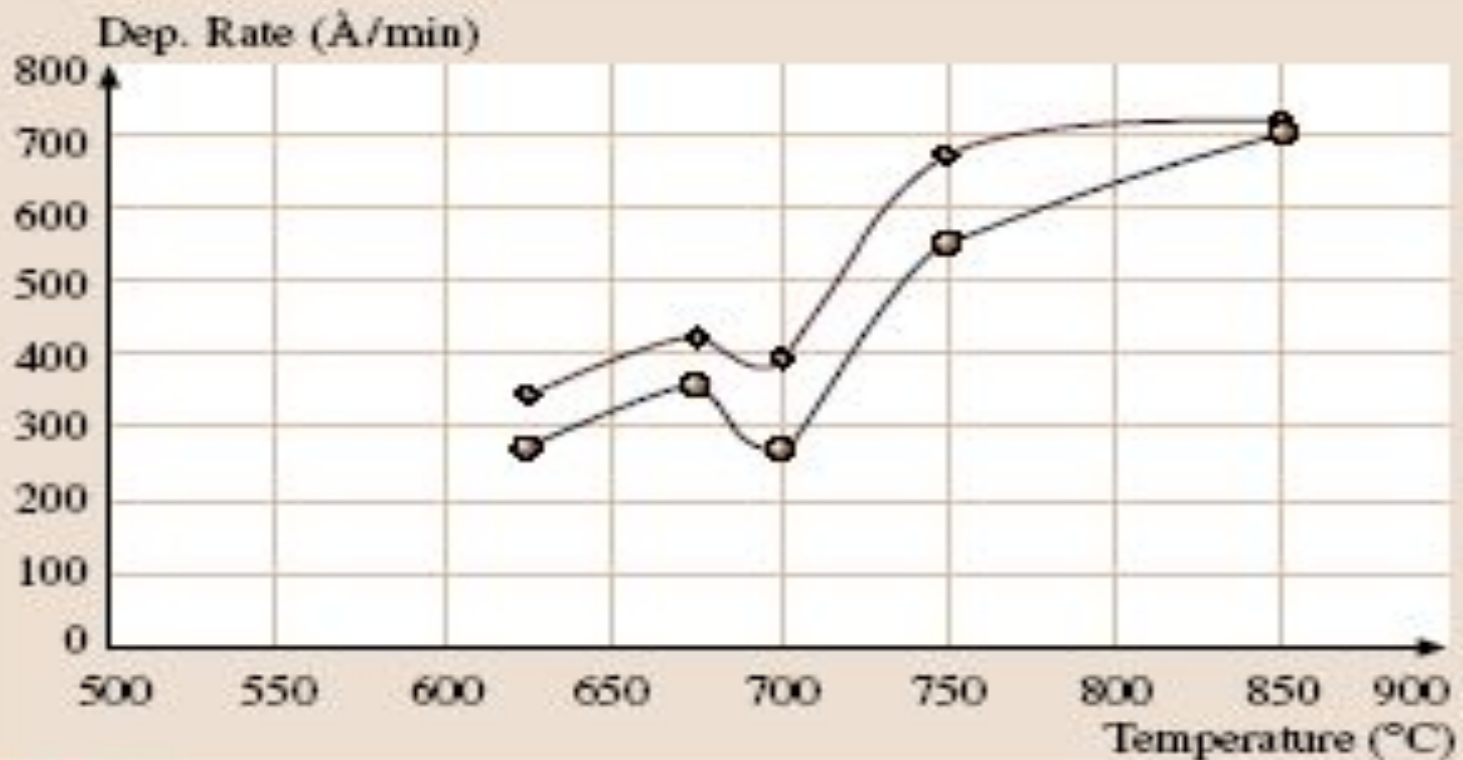


Fig. 7.3 Deposition rate versus substrate temperature for in situ boron-doped (◆) and undoped (●) polysilicon films grown by atmospheric pressure chemical vapor deposition [7.4]

- Although commonly used to produce doped polysilicon for electrostatic devices, Cao et al. have used **in situ** phosphorus-doped polysilicon films in piezoresistive strain gauges, achieving gauge factors as high as **15** for a single strip sensor.
- The **thermal conductivity** of polysilicon is a strong function of its microstructure and, therefore, the **conditions used during deposition**.
- For fine-grained (мелкозернистый) films, the thermal conductivity is about **25%** of the value of single crystal Si.

- For thick films with large grains, the thermal conductivity ranges between 50% and 85% of the single crystal value.
- Like the electrical and thermal properties of polysilicon, the as-deposited residual stress in polysilicon films depends on microstructure.
- For films deposited under typical conditions (200 mtorr, 625 °C), the as-deposited polysilicon films have compressive residual stresses.
- The highest compressive stresses are found in amorphous Si films and polysilicon films with a strong, columnar (110) texture.
- For films with fine-grained microstructures, the stress tends to be tensile.

- Annealing can be used to reduce the compressive stress in as-deposited polysilicon films.
- For instance, **compressive** residual stresses on the order of **500 MPa** can be reduced to less than **10 MPa** by annealing the as-deposited films at **1,000 °C** in a N₂ ambient.
- Recent advances in the area of rapid thermal annealing (RTA) indicate that RTA provides an effective method of stress reduction in polysilicon films.

- *Zhang* et al. reported that a 10 s anneal at 1,100 °C was sufficient to completely relieve the stress in films that originally had a compressive stress of about 340 MPa.
- RTA is particularly attractive in situations where the process parameters require a low thermal budget.

- As an alternative to high-temperature annealing, *Yang et al.* have developed an approach that actually utilizes the residual stress characteristics of polysilicon deposited under various conditions to construct polysilicon multilayers that have the desired thickness and stress values.
- The multilayers are comprised (заключать в себе) of alternating tensile and compressive polysilicon layers that are deposited in a sequential manner.

- The tensile layers consist of fine-grained polysilicon grown at a temperature of $570\text{ }^{\circ}\text{C}$, while the compressive layers are made up of columnar polysilicon deposited at $615\text{ }^{\circ}\text{C}$.
- The overall stress in the composite film depends on the number of alternating layers and the thickness of each layer.
- With the proper set of parameters, a composite polysilicon multilayer can be deposited with **near zero residual stress and no stress gradient**.

- The process achieves stress reduction reduction **without high-temperature annealing**, a considerable advantage for integrated MEMS processes.
- Many device designs **require thick polysilicon** structural layers that are not readily achievable using conventional LPCVD polysilicon, due to process-related limitations.
- For these designs, **epitaxial Si reactors** can be used to grow polysilicon films.

- Unlike conventional LPCVD processes with deposition rates of less than 100Å/min, epitaxial processes have deposition rates on the order of 1micron/min.
- The high deposition rates result from the much higher substrate temperatures ($> 1,000\text{ }^{\circ}\text{C}$) and deposition pressures ($> 50\text{ torr}$) used in these processes.
- The polysilicon films are usually deposited on SiO_2 sacrificial layers to enable surface micromachining.

- An LPCVD polysilicon **seed layer** is sometimes used to control nucleation, grain size, and surface roughness.
- As with conventional polysilicon, the microstructure and residual stress of the epi-poly films, as they are known, is related to deposition conditions.

- **Compressive** films generally have a mixture of [110] and [311] grains, while **tensile** films have a random mix of [110], [100], [111], and [311] grains.
- The Young's modulus of epi-poly measured from micromachined test structures is comparable to LPCVD polysilicon.
- Mechanical properties test structures, thermal actuators, electrostatically actuated accelerometers, and gyroscopes have been fabricated from these films.

- All of the aforementioned (вышеупомянутые) polysilicon deposition processes utilize substrate temperatures in excess (превышение) of 570 °C either during film deposition, or in postdeposition processing steps.
- As a low temperature alternative to LPCVD polysilicon, Abe et al. and Honer et al. have developed sputtering processes for polysilicon.
- Early work emphasized the ability to deposit very smooth (25 Å) polysilicon films on thermally oxidized wafers at reasonable deposition rates (191 Å/min) and with low residual compressive stresses. $t_{\text{dep}} = 7.8 \text{ s}$

- The process involved DC magnetron sputtering from a Si target using an Ar sputtering gas, a chamber pressure of **5mtorr**, and a power of **100 W**.
- The authors reported that a post-deposition anneal at **700 °C** in N₂ for **two hours** was needed to crystallize the deposited film and perhaps lower the stress.
- *Honer* et al. sought to develop a polymer-friendly, Si-based surface micromachining process based on **polysilicon sputtered onto polyimide** and **PSG sacrificial layers**.
- To improve the conductivity of the micromachined Si structures, the sputtered Si films were sandwiched between two **TiW** cladding layers (**оболочка**) .

- The device structures on polyimide were released using oxygen plasma etching.
- The processing step with the highest temperature was, in fact, the polyimide cure at 350 °C.
- To test the robustness of the process, sputter-deposited Si microstructures were fabricated on substrates containing CMOS devices.
- As expected from thermal budget considerations, the authors reported no measurable degradation of device performance.