Lecture 11

Microfabrication
– Pattern Transfer (IV)

- Wet Etching
  - Anisotropic Wet Etching
    - Orientation-Dependent Etching
    - Anisotropic Etch Rate Ratio
    - Silicon Anisotropic Wet Etching
    - Convex and Concave Corners
    - Anisotropic Etching in (100) Silicon
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    - Etch Rate
  - Etch Stops for Wet Etching
    - Electrochemical Etch Stop
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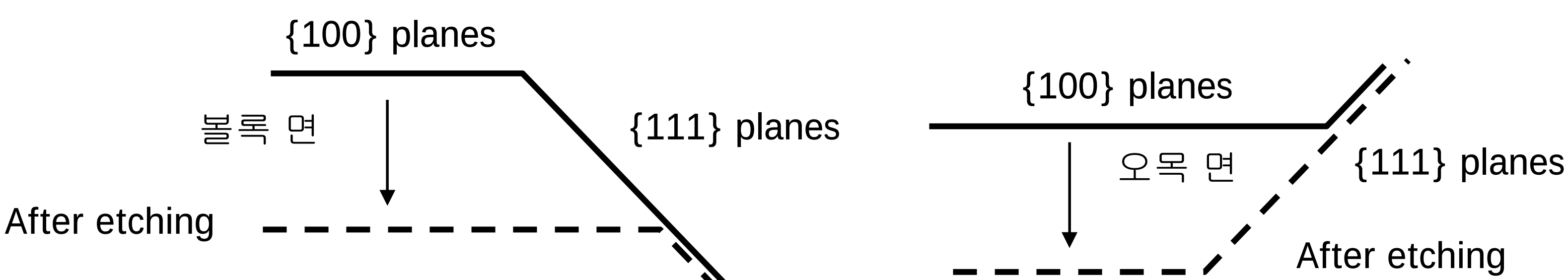
    - Dielectric Etch Stop

Orientation-Dependent Etching

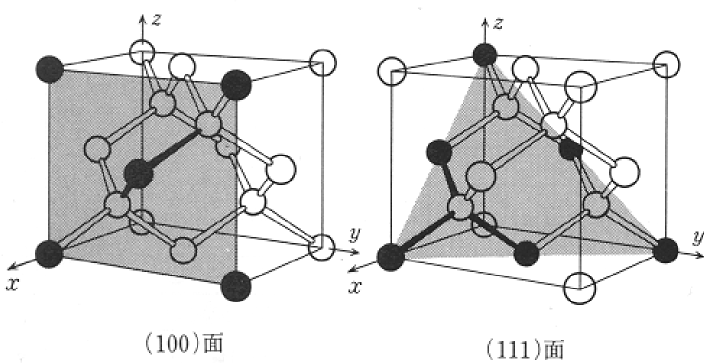
- When etching a single crystal, certain etchants exhibit orientation-dependent etch rates.
- Specially, strong bases, such as potassium hydroxide (KOH), tetra-methyl ammonium hydroxide (TMAH), and ethylene diamine pyrochatechol (EDP), exhibit highly orientation-dependent etch characteristics in silicon.
- The etching reaction is the breaking of a silicon-silicon bond with the insertion of OH groups,
- Hence is enhanced in strong bases, which have an abundance of OH^- ions.
- Ultimately, the etching forms $Si(OH)_4$, which is soluble in strong bases, along with the consumption of four molecules of water and the release of two molecules of hydrogen gas.
- Hydrofluoric acid exhibits similar orientation-dependent effects when etching single-crystal quartz.



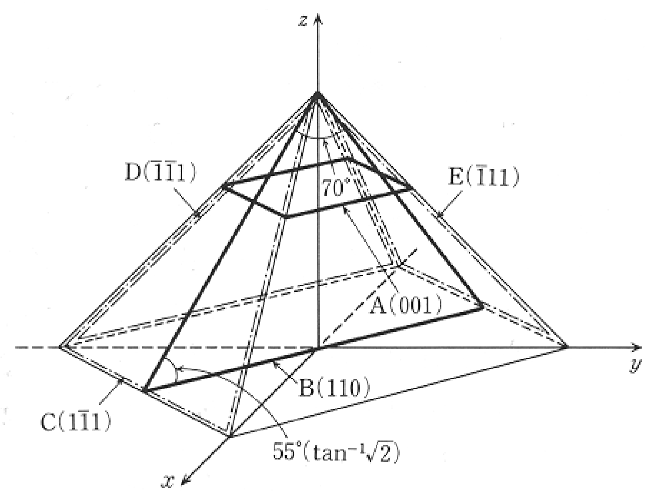
Orientation-dependent etch characteristics in silicon

Orientation-Dependent Etching in Silicon

- The mechanism responsible for orientation dependent etching in silicon is the detailed bond structure of the atoms that are revealed in different surface planes.
- {100} and {110} planes have atoms with two bond directed back into the crystal, and two bonds that must somehow “dangle” with unfulfilled valence.
- Atoms in {111} have three bonds directed back into crystal and only one bond that dangles.
- Hence atoms in {111} planes, are “more tightly bound” to the rest of the crystal.



실리콘의 결정구조



결정면의 관계

Anisotropic Etch Rate Ratio

- 결정의 절개나 결정면에서의 이방성 식각이 어떤 면에서 중지되는 현상은 원자의 면 밀도 차에 의한 결과라고 설명하고 있으나, 모든 거동을 완전히 설명하지는 못하고 있다. (Micromechanics-Etching of Silicon, Miko Elwenspoek, Ch.3 참조)
- 예를 들어, Cubic crystal인 경우(Zincblende, diamond structure), 모든 방향에 대한 원자 표면 밀도 차는 수 % 정도이어서, 실험에서 얻는 100배 이상의 이방성 또는 절개 등이 잘 설명되지 않는다.
- 이방성에 영향을 주는 다른 요소는 H_2O 분자의 흡착에 의해서 면이 가리워지는 것이 있다.
- 전형적인 이방성 비율: (111) = 1, (100) = 300~400, (110) = 600.
- 이 값들은 화학조성, 농도, 온도 등에 따라 달라진다.
- 대개 문헌과 실험을 통해서 식각율과 특성을 얻고 있다.
- 식각 특성과 식각액의 수명이 잘 파악되면 대부분의 식각액은 아주 재현성있게 식각한다.

Silicon Anisotropic Wet Etching

- 異方性 식각 : 한 방향 식각 속도가 다른 방향보다 빠른 것.
- (111)면이 다른 면보다 식각 속도가 느리다.
- 식각이 진행되면 식각이 제일 느린 면이 노출되기 시작한다.
- (100) Silicon의 오목 면 (concave) 모서리는 (111) 면이 만나서 식각이 정지되나, 볼록 면 (convex) 모서리는 무너져 깎여 들어간다 (undercut).

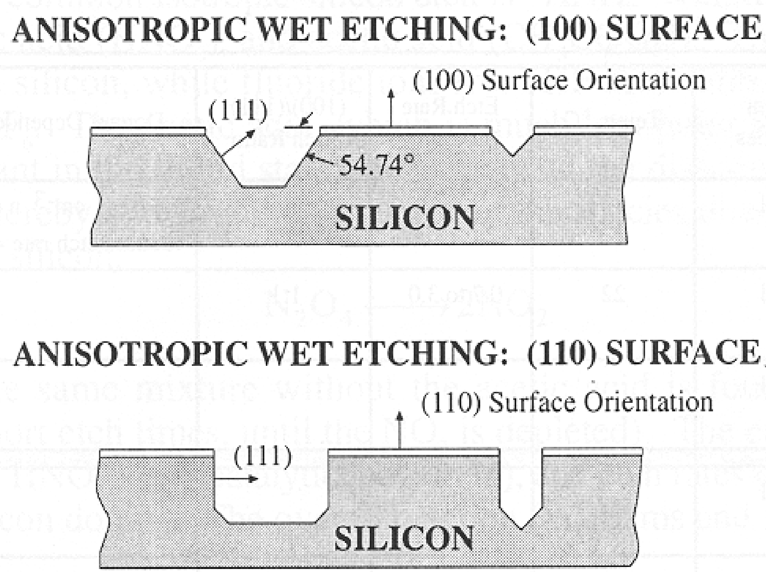


Illustration of anisotropic wet etching of (100) [top] and (110) silicon [bottom]. After Petersen (1982).

Convex and Concave Corners

- (100) Silicon의 오목 면 (concave) 모서리는 (111) 면이 만나서 식각이 정지되나, 볼록 면 (convex) 모서리는 무너져 깎여 들어간다 (undercut).
- 원하는 convex 모서리를 만들기 위해서 보상패턴에 대한 연구가 많이 수행되었다.

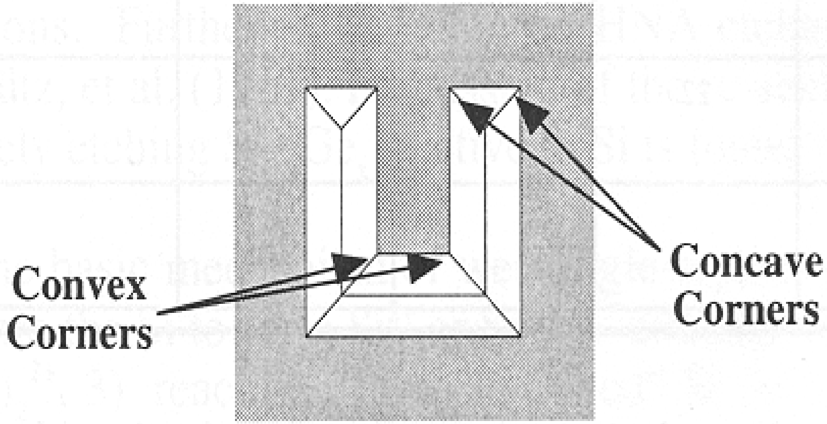
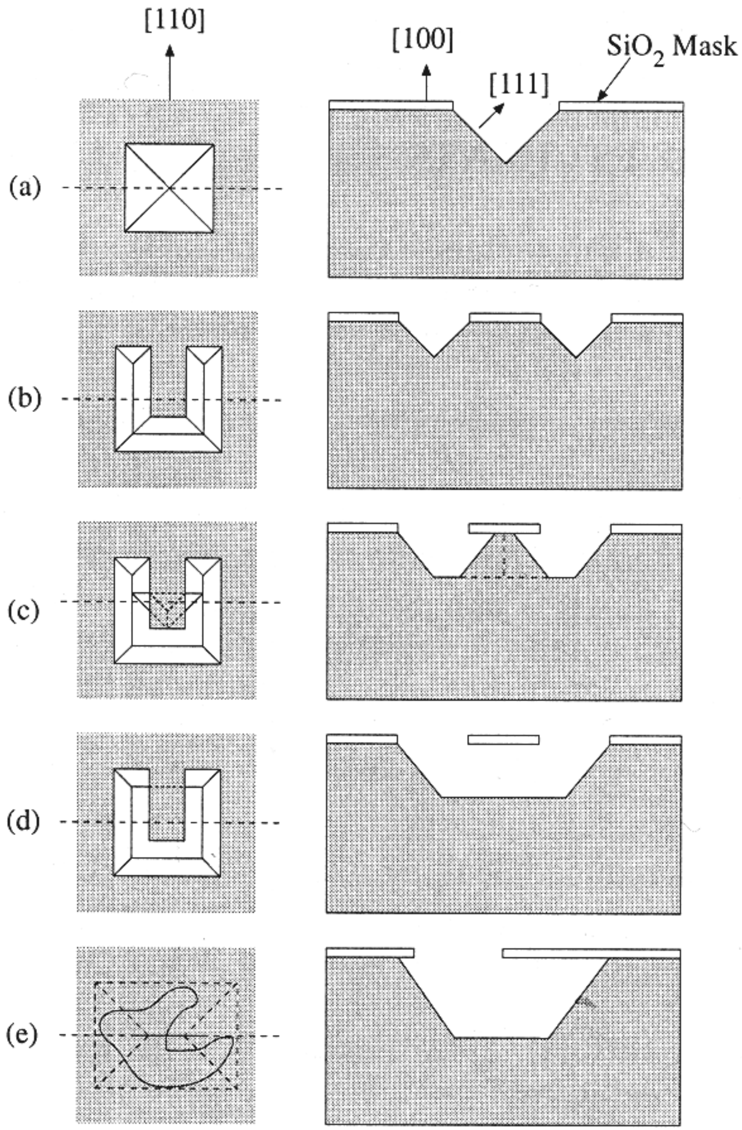


Illustration of convex and concave corners on (100) silicon. The former are rapidly undercut by anisotropic silicon etchants.

Anisotropic Etching in (100) Silicon



Some examples of anisotropic etching in (100) silicon:

(a) typical pyramidal pit, bounded by the (111) planes, etched into (100) silicon with an anisotropic etch through a square hole in an oxide mask;

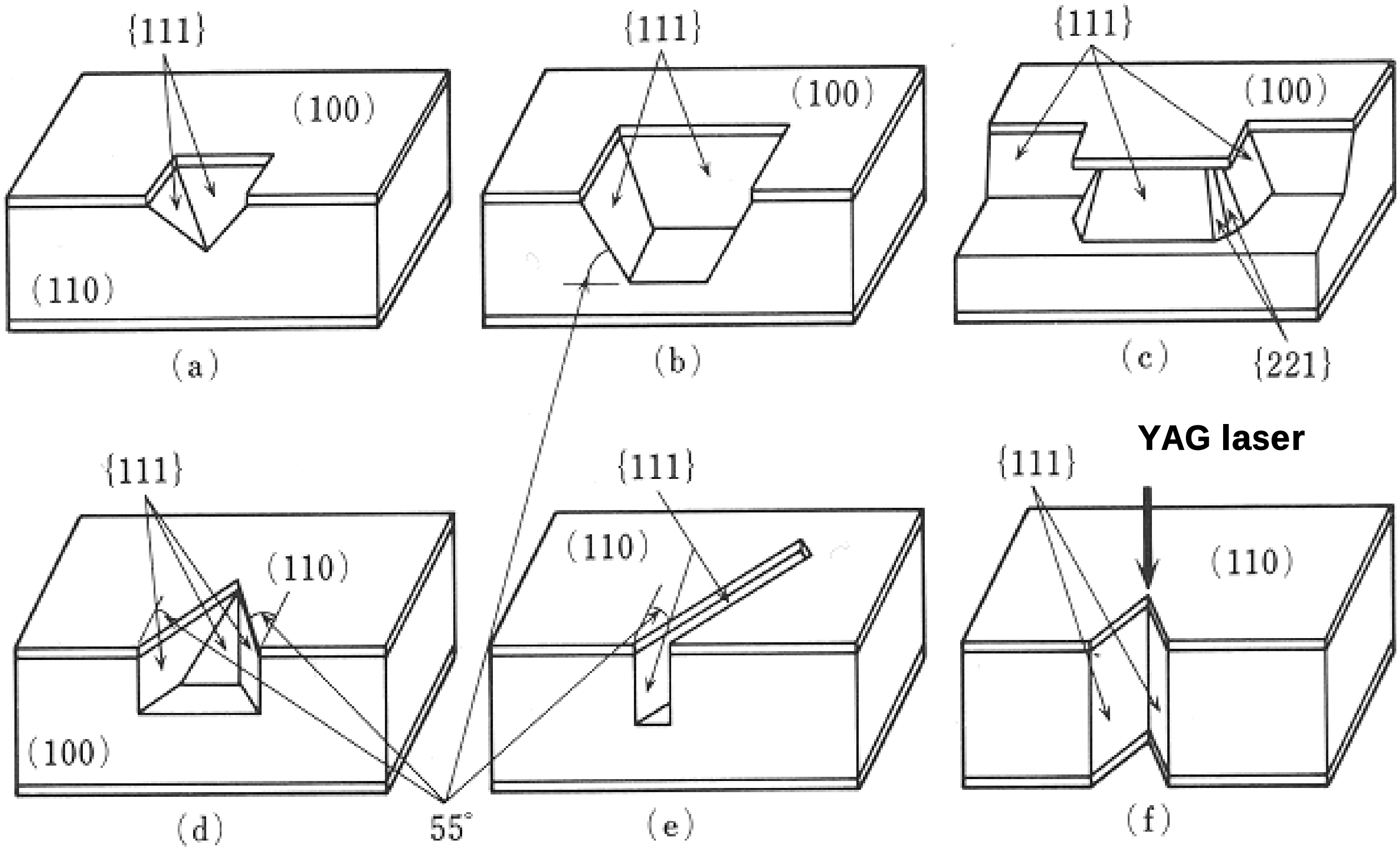
(b) cantilever mask pattern with an anisotropic etch with a slow convex undercut rate;

(c) the same mask pattern can result in a substantial degree of undercutting using an etchant with a fast convex undercut rate such as EDP (ethylene diamine pyrochatechol);

(d) further etching of (c) produces a cantilever beam suspended over the pit;

(e) illustration of the fact that anisotropic etch undercutting converges to predictable shapes after a sufficiently long time. After Petersen (1982).

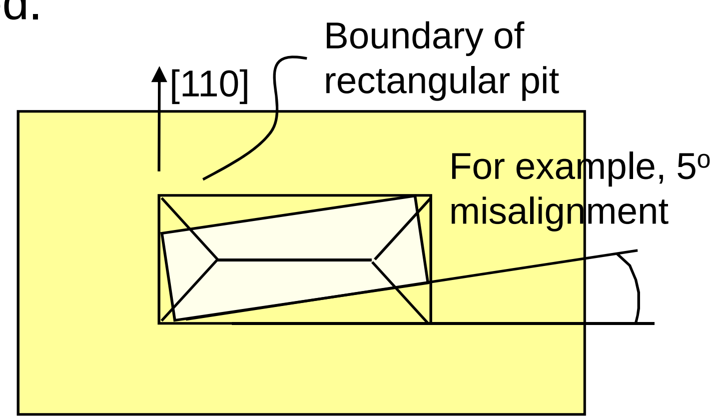
Anisotropic Etching in (100) and (110) Silicon



{100} 면, **{110}** 면 실리콘 기판의 결정 이방성 식각

Undercutting

- Suppose it is desired to align a rectangular feature so that its edges are perfectly parallel to <110> direction but, because of a lithographic error, the pattern is actually rotated directions a few degrees off target.
- The bounding rectangular etch pit is what determines the final etched shape.
- In practice, wafer flats identify a [110] direction to better than one degree.
- If extremely accurate alignment is needed, then it is necessary to pre-etch an alignment feature into the wafer using the anisotropic etchant so that the exact <110> in-plane directions are delineated.
- An example of such a feature would be a circle.
- In an anisotropic etchant, the circular mask feature tends to form a square with edges tangent to the circle along <110> directions.



The effect of misalignment is to enlarge the etched region.

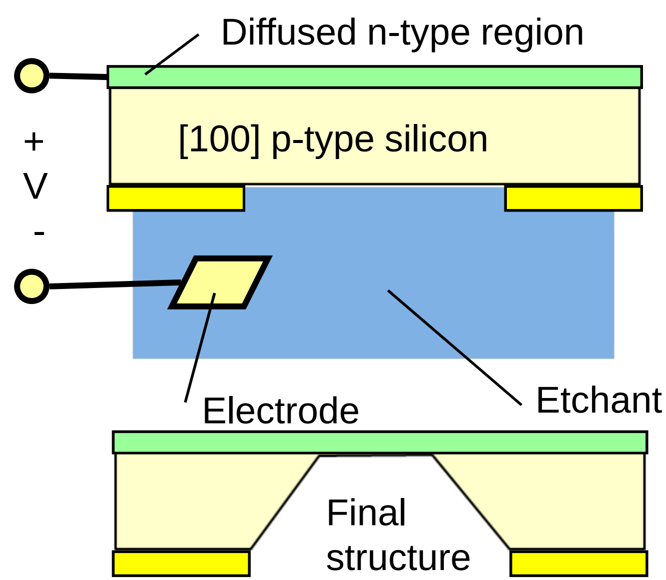
Etch Rate

- The etch rate in anisotropic etchants decreases rapidly when etching heavily boron-doped material in excess of about 5 x 10^{19} cm^{-3}.
- This means that heavily doped p-type silicon (p+ silicon) can be used as a masking material.
- Because anisotropic etches require long exposure to the etchant, the etch-rate ratio of the fast-etching planes to the {111} planes is extremely important.
- In 20 wt. % solution of KOH at 85^{o}C, the etch rate of the {100} planes is 1.4 micron/min, and the selectivity to the {111} planes is 400:1.
- The etch rate of the masking layer is also important.
- Possible masking materials for KOH are silicon nitride, which hardly etches at all, SiO_2, which etches at about 1.4 nm/min, and p+ silicon, offers between a 10:1 and 100:1 reduction in etch rate over lightly doped silicon, depending on the etchant and the etch temperature.
- As an example, to etch all the way through a 500 micron thick wafer with 20 wt.% KOH at 85 ^{o}C, it takes 6 hours.
- It requires 504 nm silicon dioxide or 50 nm silicon nitride.
- Processes that include these deep etches must be designed with both absolute etch rate and mask etch rate in mind.

Electrochemical Etch Stop

- When a silicon wafer is biased with a sufficiently large anodic potential relative to the etchant, it tends to oxidize (electrochemical passivation).
- The passivation step is a redox reaction and requires current.
- If the supply of that current is blocked with a reverse biased pn junction, the passivation cannot occur and the etching can proceed.
- As a result,the p-silicon remains unpassivated and hence etches.
- Finally, p-silicon etched away, and then the current stats to flow.
- The current makes a passivation layer on the n-type region, and etching stops.

- A p-type wafer has a diffused n-region at its upper surface.
- The depth of the junction can be accurately controlled by the combination of ion implantation and drive in.
- The resulting diaphragm thickness is equal to the depth of the original junction.



Illustrating the electrochemical etch stop.

Diode Junction Etch-Stop

- p-type silicon은 OCP (Open-circuit potential)에서 floating되어 있고, 빨리 식각된다.
- p-n junction은 역전압(n-type silicon에 양의 전압)이 걸려 있어서, diode가 식각되어 버리면 양전압이 걸린 n-type silicon이 노출되면서 식각이 중지된다.
- n-type silicon은 passivation potential 이상의 전압이 걸려 있다. 그래서 p-type silicon이 식각되면 노출된 n-type silicon에는 전류가 흐르면서 산화가 일어나고 즉각 passivation되어 식각을 중지시킨다.
- 전기적으로 설명하면 전압강하는 p-n junction에서 일어나고, p-n diode가 파괴될 때까지 p-type silicon에 전압이 걸려 있게 된다. p-type silicon이 식각되어 없어지면 n-type silicon에 산화막이 생기면서 식각이 중지된다.
- 정확한 두께 제어가 가능하다.

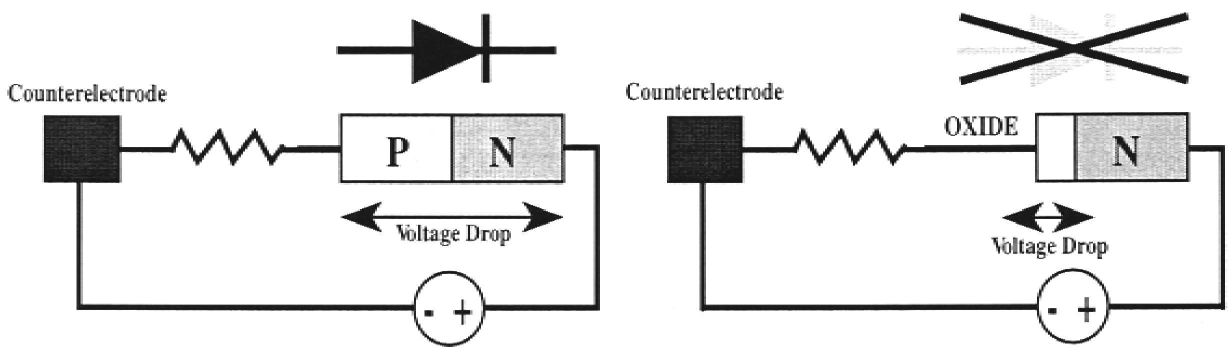


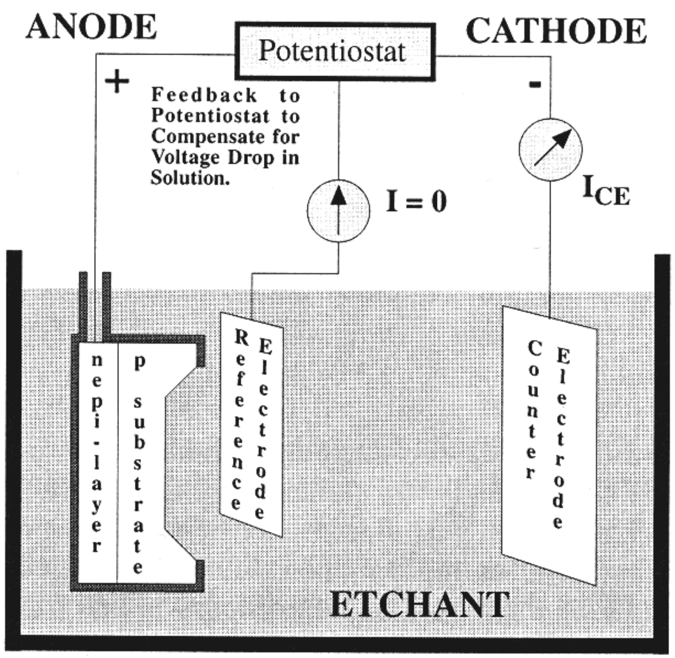
Illustration of diode junction etching

Thickness of Diaphragm

- A p-type wafer has a diffused n-region at its upper surface.
- The depth of the junction can be accurately controlled by the combination of ion implantation and drive in.
- The resulting diaphragm thickness is equal to the depth of the original junction, at least ideally.
- It is necessary to control the junction leakage and current supply paths to be certain,
- **first,** that there is no path way that can provide enough current to passivate the p-region,
- **and second,** that once the junction is reached, all features have enough current supply so that they passivate at the same point.

Apparatus of Electrochemical Etch Stop

- p-type silicon 웨이퍼에 p-n junction을 만들고 n-type silicon 표면에서 식각을 중지시키는 방법(즉, diode가 파괴될 때까지 식각 진행).
- Potentiostat는 전압을 조절. 기준 전극으로부터의 전압을 읽어서 웨이퍼와 용액간의 전압을 조절하는 역할을 담당.
- 기준 전극은 웨이퍼에 아주 가까이 위치시켜 용액에서의 전압강하를 측정한다.



A standard three-electrode system for electrochemical etch-stops.
After Kloeck, et al. (1989).

- In practice, the wafer is immersed into the etchant with only an edge available for contact.
- The top n-type surface would typically be protected with additional mask-layer material.
- In addition, contact to the p-type layer is often made to assure that any leaking current through the pn junction can be captured before it causes passivation.

p+ Etch-Stop

- Highly p-doped (p+) silicon 영역에서는 식각율이 급격히 감소하므로 etch stop layer로 사용.
- This greatly simplifies the tooling required to perform the etch.
- However, etch-rate selectivity is not quite as high as for passivating oxides.
- Furthermore, the p++ diaphragm will have residual tensile stress that might affect the performance of any device, such as a pressure sensor, that depends on the mechanical properties of structure.
- Silicon dioxide 등의 마스크로 원하는 영역에만 doping이 가능.
- Silicon을 식각하면 doping된 부분만 남는다 (깊이 최대 15 ㎛ 정도).

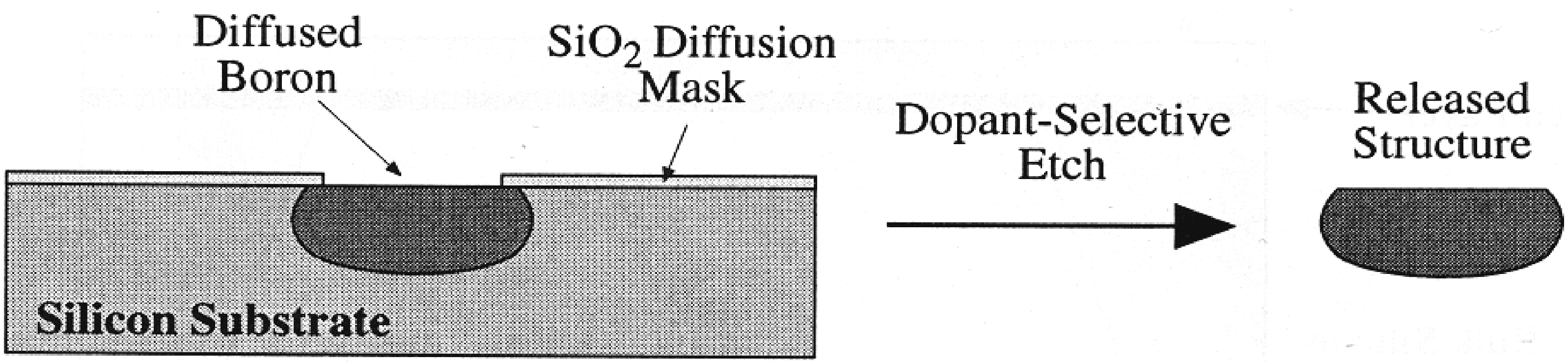
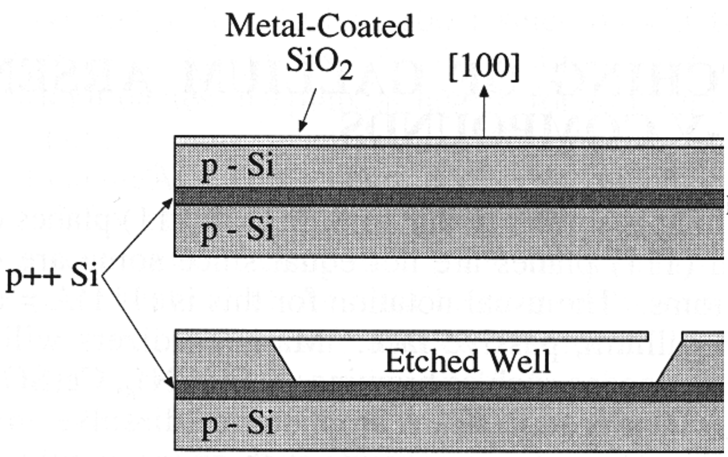


Illustration of the use of heavy boron doping with a dopant-selective etch to form free structures defined by the extent of the boron diffusion at a dopant-stopping concentration.

(continued)

p+ Etch Stop Layer

- p+ epitaxial layer : EDP, TMAH, KOH 식각액 등과 같이 사용됨.
- p+ epitaxial layer에 germanium를 더해 stress를 보상한다.
  (boron은 tensile stress를 만드는데 germanium 이를 보상).



An example of the use of a buried etch-stop layer to fabricate movable cantilevers. After Petersen (1982). The silicon is anisotropically etched from under the patterned, metal-coated silicon dioxide to release the beams. EDP etching automatically terminates on the buried p++ layer

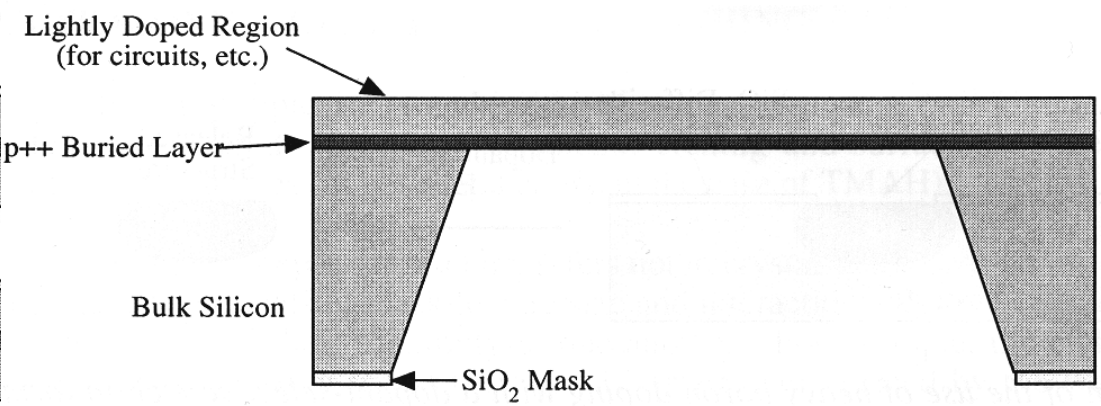
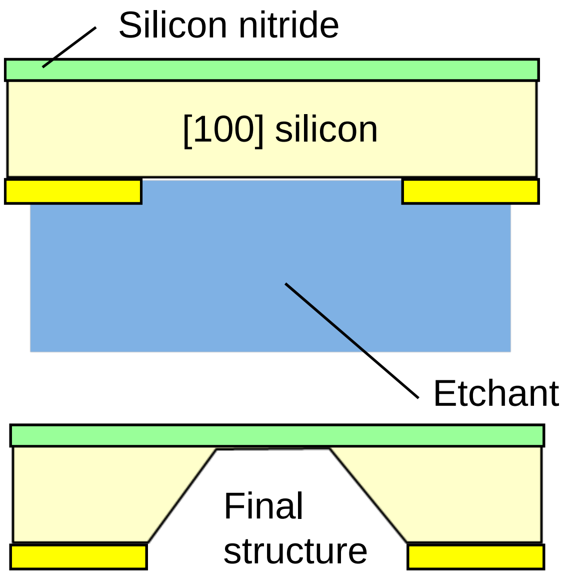


Illustration of the use of a buried etch-stop layer to fabricate a membrane with precisely controlled thickness

Dielectric Etch Stop

- If the n-layer were replaced by a material that is not etched, for example, silicon nitride, then the result of the anisotropic etch is a silicon nitride diaphragm suspended over a hole through the silicon.
- LPCVD silicon nitride is very brittle, and has a very high residual tensile stress, making it prone to fracture.
- However, if the ratio of dichlorosilane to ammonia is increased during silicon nitride deposition, a silicon-rich nitride layer is deposited which has lower stress.
- Membranes of silicon-rich nitride can be used as the basis for mechanical devices.
- Masks for X-ray lithography can also be made in this fashion, depositing gold on the membrane to create the masking regions.



Illustrating the dielectric etch stop.