A bare silicon wafer is oxidized for 120 minutes at 1100 °C in dry O₂ followed by 30 minutes at 920°C in wet O₂. What is the final thickness? If the oxide is patterned (i.e. etched away in certain areas) between the first and second oxidation, what will be the thickness of the oxide in the patterned region?

After 2 hours at 1100°C: Oxide thickness = 196 nm. After an additional 30 min. at 920°C: Oxide thickness = 298 nm. Thickness in the patterned region (due to just 30 min at 920°C): = 155 nm

• One micron of silicon dioxide is grown on a wafer. You subsequently determine that the oxidation step has caused the doping concentration near the surface to rise (compared to the bulk). Explain why this has happened, and what this means about the segregation coefficient and the diffusion constant of this dopant.

A rise in concentration of dopant at the surface (of the silicon) relative to the bulk is a result of the segregation coefficient (m) being greater that one, and the diffusion of the dopant in the oxide being relatively slow.

$$\frac{\mathbf{x_O^2} - \mathbf{x_i^2}}{\mathbf{B}} + \frac{\mathbf{x_O} - \mathbf{x_i}}{\mathbf{B}/\mathbf{A}} = \mathbf{t}$$







• Briefly describe 3 beneficial physical or chemical qualities of SiO₂.

Answers

Diffusion barrier for P, B, As; therefore, can be used as a mask.

Etched by HF which does not attack Si; allows creation of a mask from SiO₂.

High electrical resistivity; useful as insulator.

Epitaxial, clean interface; reproducible electrical properties.

High dielectric breakdown; stable under high voltage.

Stable to 900°C or 10⁻⁹ Torr; unaffected by subsequent processing.

• There are two general types of solutions to the diffusion equation that are relevant to processing, one Gaussian and the other a complementary error function.

i) List the two boundary conditions and one initial condition for the Gaussian solution and sketch the form of this solution for small time and a later time.

ii) List the two boundary conditions and one initial condition for the complementary error function solution and sketch the form of this solution for small time and a later time

- You want to create a shallow p-n junction near the surface of a doped Si wafer and need to maintain the highest possible dopant concentration near the wafer surface. You have access to B and P sources for CVD deposition or doping from the vapor/gas phase and a suitable reaction chamber.
- a. Would you prefer to use B or P as a dopant? Explain.P because it has a higher solubility than B at 1100 K.

b. Which type of Si wafer would you then start with, p-type or n-type?P is donor so you need an acceptor-doped, p-type Si wafer.

c. Would you prefer to use a pre-deposited film (B or P) then diffuse it in at 1100 K or expose the wafer to the appropriate gas phase (diborane or phosphene) while diffusing at 1100 K? Explain and sketch profiles in each case (below) showing profiles in each figure for 2 different diffusion times.

Prefer to diffuse from a constant vapor source (if you can get vapor dopant concentration, C_0 , as high as its solubility limit in Si) so surface concentration in Si remains at C_0 for all times; complementary erf solution.



• A Ph. D. student just got her wafers back from boron ion implantation, and she wants to check the profile of boron in the top 100 nm of the silicon. Which analysis technique would you suggest she use, and why?

For normal ion implantation of dopants, dopant concentration is in the range of 1e¹⁵ to 1e¹⁹ cm⁻³. SIMS is able to resolve this range of concentration and obtain depth profiles in the top 100 nm.

• Your first effort involved a 10-minute diffusion process and put the junction depth at twice the desired depth. On your next run at the same temperature, how long should your diffusion process last? Why?

The junction depth advances with time like the diffusion length, $\mathbf{a} = 2(Dt)^{1/2}$. So you would decrease your time four-fold to get half the junction depth, namely to t = 2.5 min instead of 10 min.

• Explain in a few words and with a sketch why diffusion is generally accelerated in a region that is already highly doped with that species.

Separation of mobile and fixed N_D charges in highly doped region E z results in an internal electric field that always acts to drive the dopant farther into the material.



• Explain briefly how this effect might be relevant to your desire to create a high dopant concentration at the surface while maintaining a shallow junction depth.

This effect always results in a more square diffusion profile, i.e. greater diffusion length at high concentrations and smaller a at lower concentration. This makes it easier to maintain a high surface concentration of dopant with a sharp drop off to keep the junction as shallow as possible.

- One of your colleagues later told you that she had read about a device like your shallow junction/high-surface concentration one, but made instead using ion implantation and getting a junction depth considerably less than yours. She could not recall the species implanted.
- a. Was the implanted species more likely B, P, or As? Explain.

Most likely used As ion implantation, because it has the shortest range of the three at a given ion energy (see figure).

• Describe the likely dominant stopping mechanism (nuclear or electronic) for your answer in a) and explain why.

As implants are stopped mainly by nuclear scattering because of its large mass relative to P or B. The latter reach a higher velocity at a given energy and so are more dominated by electronic stopping, especially so for B. • Phosphorus is implanted at 100 keV to a dose of Q = $2.5 \ 10^{14} \text{ cm}^{-2}$ in a p-type Si wafer, N_A = 10^{18} cm^{-3} . (Use data below for implanting into Si).



- a. At what depth is the implanted P concentration a maximum?
- b. What is the peak phosphorus concentration?
- c. What is the depth of the junction before diffusion?
- d. What happens to the value of C_p and its location if the implant is subjected to a diffusion process at an elevated temperature?

e. With what mathematical form does the junction depth evolve with time upon diffusion at an elevated temperature?

- a. From figure, $R_p = 1250 \text{ Å} (1.25 \times 10^{-5} \text{ cm}).$
- b. $\Delta R_{\rm p} = 350$ Å, $\tilde{C}_{\rm p} = Q/[\sqrt{(2\pi)} \Delta R_{\rm p}] = 2.85 \times 10^{19}$ cm⁻³.
- c. The implant concentration profile is equal to the background acceptor

concentration:
$$C(x) = C_p \exp\left(-\frac{(x - R_p)^2}{2\Delta R_p^2}\right) = 10^{18}$$
. Inverting to solve for x

gives:
$$x = R_p + \sqrt{2\Delta R_p^2 \ln(28.5)} = 0.22 \ \mu m$$

- d. The value of C_p decreases but its position remains the same (to first order) upon diffusion. If you took "its location" to mean that of the junction, the answer is "junction moves deeper into Si".
- e. The implant profile advances deeper into the wafer like \sqrt{Dt} .

a) What is the intrinsic carrier concentration in Si at 1100 °C? b) Calculate the effective diffusivity (including first-order, charged-vacancy corrections) for As impurities in Si at 1100 °C for two cases:

i) $C_{As} = 10^{15} \text{ cm}^{-3}$ and ii) $C_{As} = 10^{19} \text{ cm}^{-3}$ iii) $C_{As} = 10^{20} \text{ cm}^{-3}$ $(D_{0}^{\circ} = 0.066 \text{ cm}^{2}/\text{s}; E^{\circ} = 3.4 \text{ eV} D_{0}^{\circ} = 12 \text{ cm}^{2}/\text{s}; E^{\circ} = 4.0 \text{ eV})$ c) What is the diffusion length in each case for t = 1 hr.

 $(C = N_D - N_A)$ $N_{\rm D} + p - N_{\rm A} - n = 0$ (σχέση ηλεκτρικής ουδετερότητας) και p n = n_i^2 (καλείται συνήθως νόμος δράσης μαζών),

με το εξής αποτέλεσμα:

$$(N_D > N_A C^{\sim} N_D) \qquad (N_A > N_D)$$

$$\frac{\mathbf{n}}{\mathbf{n}_{i}} = \frac{\mathbf{C}}{2\mathbf{n}_{i}} + \sqrt{1 + \left(\frac{\mathbf{C}}{2\mathbf{n}_{i}}\right)^{2}} \qquad \frac{\mathbf{p}}{\mathbf{n}_{i}} = \frac{-\mathbf{C}}{2\mathbf{n}_{i}} + \sqrt{1 + \left(\frac{\mathbf{C}}{2\mathbf{n}_{i}}\right)^{2}}$$
$$\frac{\mathbf{n}}{\mathbf{n}_{i}} = \frac{\mathbf{n}_{i}}{\mathbf{p}}$$

Simplifications: $n/n_i = C/n_i$ (C >> n_i), $n/n_i = 1$ (C < n_i)

$$D_D^{eff} = D^0 + D^- \frac{n}{n_i}$$
 $D_A^{eff} = D^0 + D^+ \frac{p}{n_i}$

Diffusion length = $2 (Dt)^{1/2}$

Do exp(-E/kT)

You start with a uniformly doped ($N_A = 10^{17} \text{ cm}^{-3}$), p-type silicon wafer. Then a predeposition of phosphorus is made at 1000 °C to a concentration at the surface equal to its solubility limit (2. 10^{20} cm^{-3}). This process takes 2 min and $D_P=4.7 \text{ exp}$ (-3,68/kT).

a) What is the surface dose, Q, of phosphorus?

After the deposition, the surface of the Si was sealed and a "drive-in" anneal was made at 1100 °C.

b) For how long must the "drive-in" anneal be carried out to put the n-p junction 0.4 microns beneath the surface?

c) What is the surface concentration, Cs(0, t), after "drive-in"?

$$D_{1000} = 2.8 \ 10^{-15} cm^2 s^{-1} \qquad \qquad D_{1100} = 1.4 \ 10^{-14} cm^2 s^{-1}$$

a)
$$Q = \frac{2C_s}{\sqrt{\pi}}\sqrt{Dt} = \frac{4.10^{20}}{\sqrt{\pi}} cm^{-3}\sqrt{120 \ s} \ (2.8 \ 10^{-15}) cm^2 s^{-1} = 10^{14} \ cm^{-2}$$

b)
$$10^{17} = \frac{Q}{\sqrt{\pi Dt}} \exp(-\frac{(0.4 \ 10^{-4})^2}{4Dt})$$

c)
$$C_S(0,t) = \frac{Q}{\sqrt{\pi Dt}} = \frac{10^{14}}{\sqrt{\pi (1.4 \ 10^{-14})t}}$$

• An 80 keV, 5×10^{13} cm⁻² boron implant is performed into bare silicon. A subsequent anneal at 950°C (D_B = 4.24 × 10⁻¹⁵ cm² sec⁻¹) is performed for 60 min.

a) Can the annealed profile evolution be described by the formula :

$$C(z,t) = \frac{Q}{\sqrt{\pi Dt}} \exp\left[-\frac{z^2}{4Dt}\right]$$

(a) This formula applies only when the initial dose is introduced as a delta-function near the surface, or receives sufficient diffusion (Dt) that the delta-function approximation is reasonably valid. The boron implant has a range of 0.15 μ m and a standard deviation of 0.08 μ m.

 $\Delta R_p^2 = 6.4 \times 10^{-11} \text{ cm}^2$ and 2Dt = 3 X 10⁻¹¹ cm² are comparable, so the profile does not receive a large amount of diffusion compared to the initial distribution.

The simple delta-function approximation is not valid.

(b) Assume that all the dopants remain in the silicon and that none evaporates to the ambient. By considering a reflecting boundary, calculate the surface concentration after a 60 min, 950°C anneal.

(b) The formula for diffusion in an infinite medium is

$$C(x,t) = \frac{Q}{\sqrt{2\pi \left(\Delta R_p^2 + 2Dt_{eff}\right)}} exp \left(-\frac{\left(x - R_p\right)^2}{2\left(\Delta R_p^2 + 2Dt_{eff}\right)}\right)$$

We can assume an identical imaginary (or virtual) diffusion profile from the ambient side of the interface, contributing to the surface concentration and hence doubling it.

$$C = \frac{5 \times 10^{-13}}{\sqrt{2\pi \left(6.4 \times 10^{-11} + 3 \times 10^{-11}\right)}} \exp \left(-\frac{\left(0.15 \times 10^{-4}\right)^2}{2\left(6.4 \times 10^{-11} + 3 \times 10^{-11}\right)}\right)$$
$$C = 6.2 \times 10^{17} \text{ cm}^{-3}$$

Boron atoms are incident to the surface with energy 40 keV and the dose was 5 x 10^{15} cm⁻². Calculate and plot the concentration of boron atoms as a function of x (one dimension into the Si wafer) following ion implantation. The sample is then subjected to an anneal for 37 minutes at 950 °C; plot the dopant concentration after the anneal. If the silicon substrate has a background concentration of 2 x 10^{15} cm⁻³, at what depth is the p-n junction?

40 keV:
$$R_p = 0.14 \ \mu m$$
, $\Delta R_p = 0.06 \ \mu m = 60 \ nm$ $D_B = 6.10^{-16} \ cm^2 \ s^{-1}$

$$(x) = C_p \exp\left(-\frac{\left(x - R_p\right)^2}{2\Delta R_p^2}\right) = \frac{Q}{\Delta R_p \sqrt{2\pi}} \exp\left(-\frac{\left(x - R_p\right)^2}{2\Delta R_p^2}\right)$$

$$2\sqrt{Dt} = 2.10^{-6} = 20 \ nm$$

С

$$C(x,t) = \frac{Q}{\sqrt{2\pi(2Dt + \Delta R_p^2)}} \exp\left(-\frac{(x - R_p)^2}{2(\Delta R_p^2 + 2Dt)}\right) \qquad 2.10^{15} = C(x_j, 37min)$$

Sketch a process flow that would result in the structure shown in Figure by drawing a series of drawings similar to those in this chapter. You only need to describe the flow up through the stage at which active device formation starts since from that point on, the process is similar to that described in this chapter.



We can follow many of the process steps used in the CMOS process flow in Chapter 2. The major differences are that an epi layer is needed, only one well (P well) used, and the device structures are considerably simplified from those in the text because there are no LDD regions etc.



The first step is to grow the blanket epi layer shown in the final cross-section. A heavily doped P+ substrate is chosen and a lightly doped boron epitaxial layer is grown uniformly on its surface.



Mask #1 patterns the photoresist. The Si_3N_4 layer is removed where it is not protected by the photoresist by dry etching. Since the technology uses field implants below the field oxide, a boron implant is used to dope these P regions.



During the LOCOS oxidation, the boron implanted regions diffuse ahead of the growing oxide producing the P doped regions under the field oxide. The Si_3N_4 is stripped after the LOCOS process.



Mask #2 is used to form the N well. Photoresist is used to mask the regions where NMOS devices will be built. A phosphorus implant provides the doping for the N wells for the PMOS devices



A high temperature drive-in completes the formation of the N well.



After spinning photoresist on the wafer, mask #3 is used to define the NMOS transistors. A boron implant adjusts the N channel V_{TH} .



After spinning photoresist on the wafer, mask #4 is used to define the PMOS transistors. A phosphorus or arsenic implant adjusts the P channel V_{TH} . (Depending on the N well doping, a boron implant might actually be needed at this point instead of an N type implant, to obtain the correct threshold voltage.)



After etching back the thin oxide to bare silicon, the gate oxide is grown for the MOS transistors.



A layer of polysilicon is deposited. Ion implantation of phosphorus follows the deposition to heavily dope the poly.



Photoresist is applied and mask #5 is used to define the regions where MOS gates are located. The polysilicon layer is then etched using plasma etching.



Photoresist is applied and mask #6 is used to protect the PMOS transistors. An arsenic implant then forms the NMOS source and drain regions.



After applying photoresist, mask #7 is used to protect the NMOS transistors. A boron implant then forms the PMOS source and drain regions.

At this point we have completed the formation of the active devices, except for a final high temperature anneal to activate the dopants and drive in the junctions to their final depth. The rest of the process flow would be similar to the CMOS flow in the text.