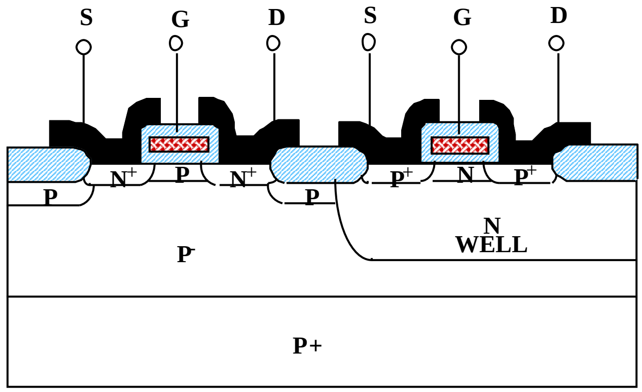
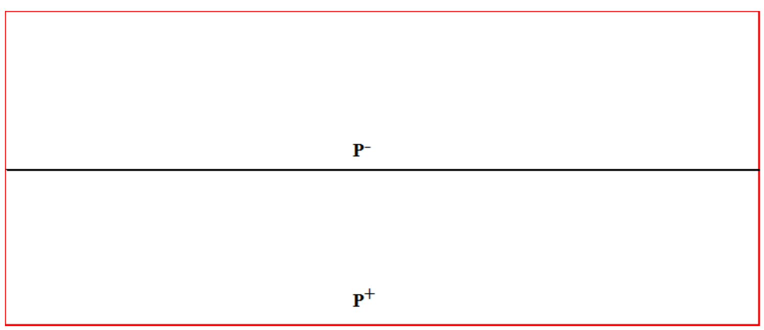
Problem 1

Answer:

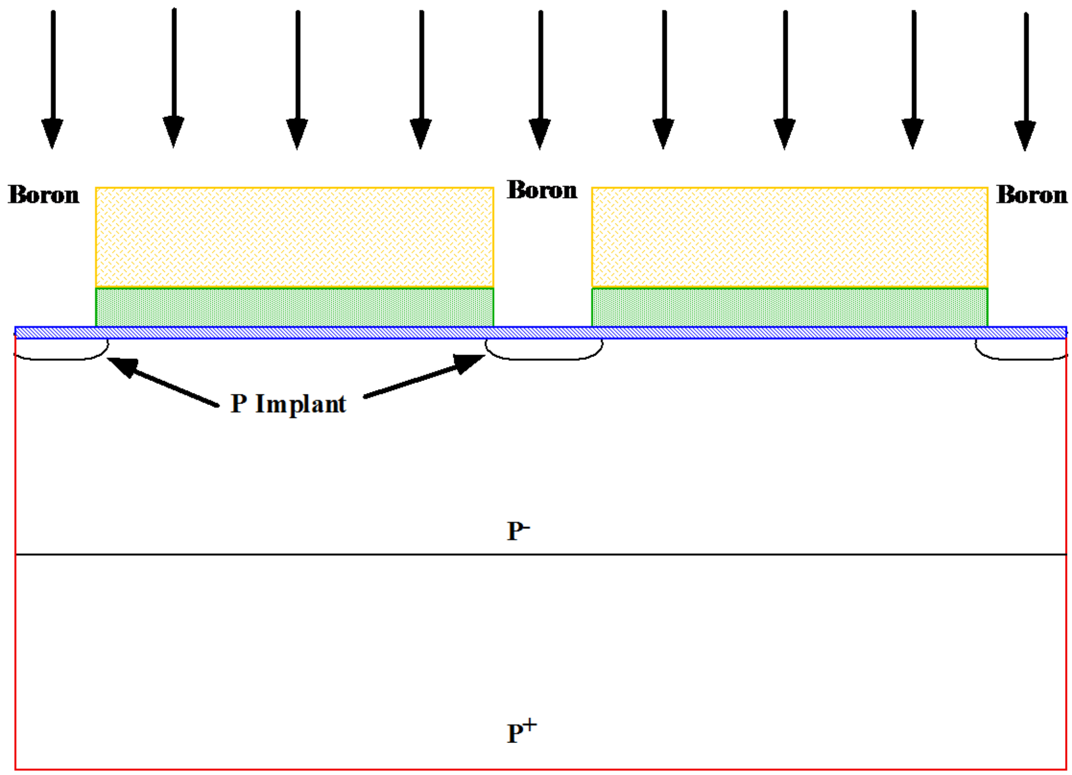
The CMOS technology we need to realize is shown below.



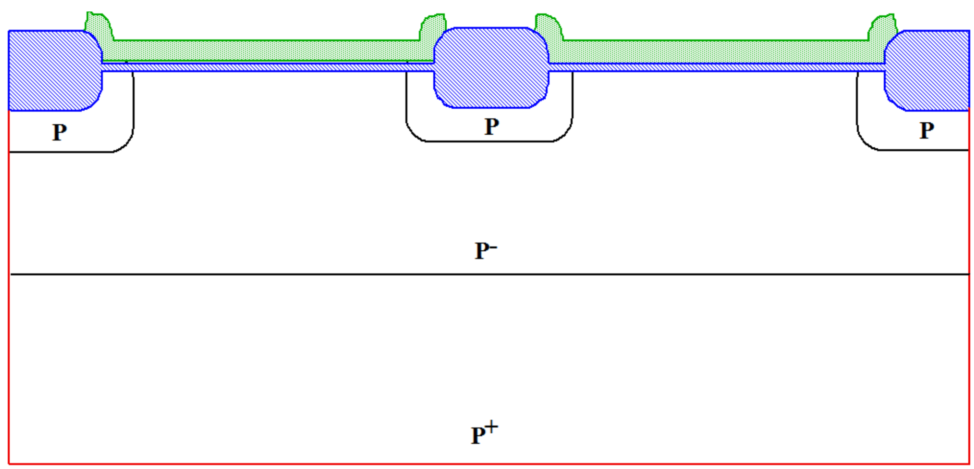
We can follow many of the process steps used in the CMOS process flow in notes. The major differences are that an epi layer is needed, only one well (P well) used, and the device structures are considerably simplified from those in the text because there are no LDD regions etc.



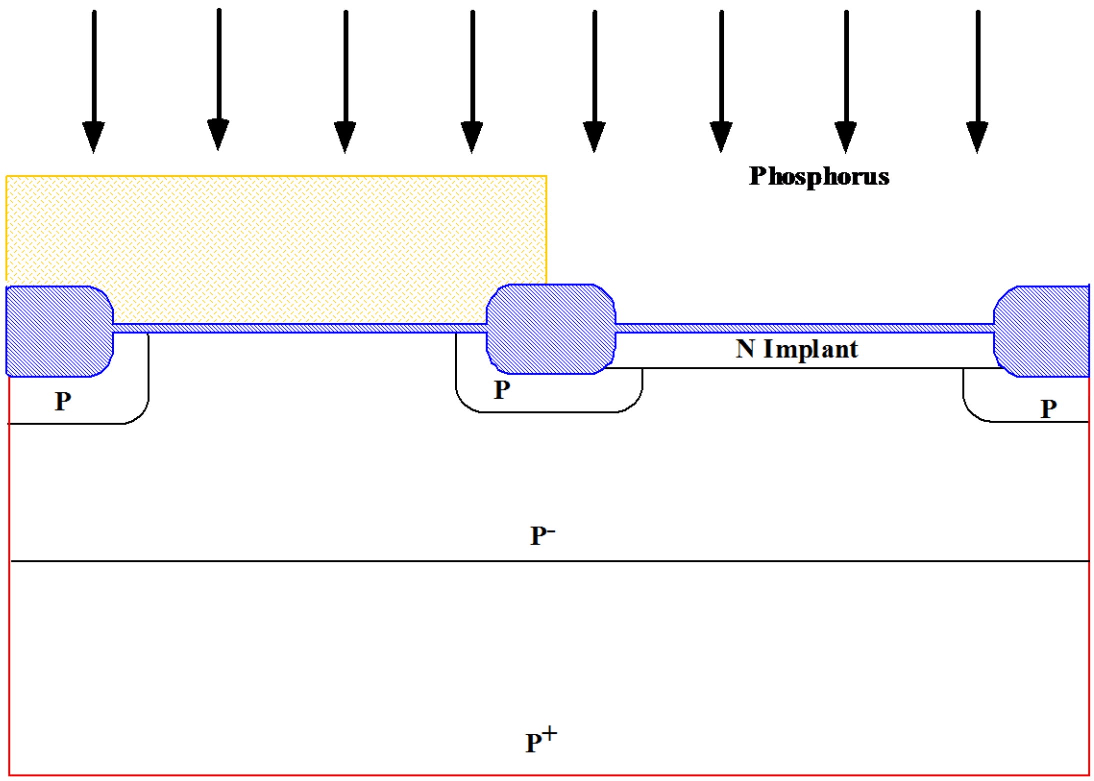
The first step is to grow the blanket epi layer shown in the final cross-section. A heavily doped P^+ substrate is chosen and a lightly doped boron epitaxial layer is grown uniformly on its surface.



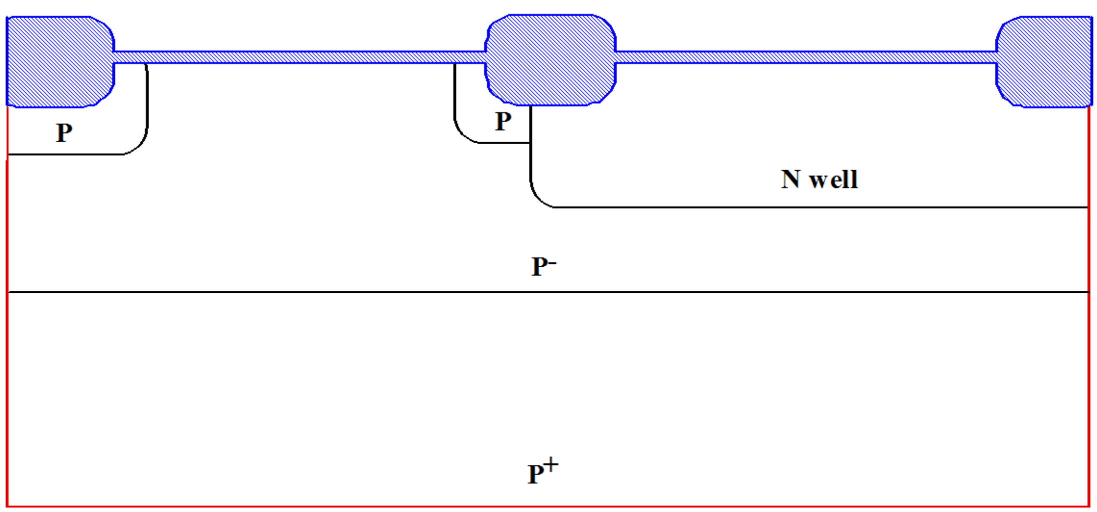
Mask #1 patterns the photoresist. The Si_3N_4 layer is removed where it is not protected by the photoresist by dry etching. Since the technology uses field implants below the field oxide, a boron implant is used to dope these P regions.



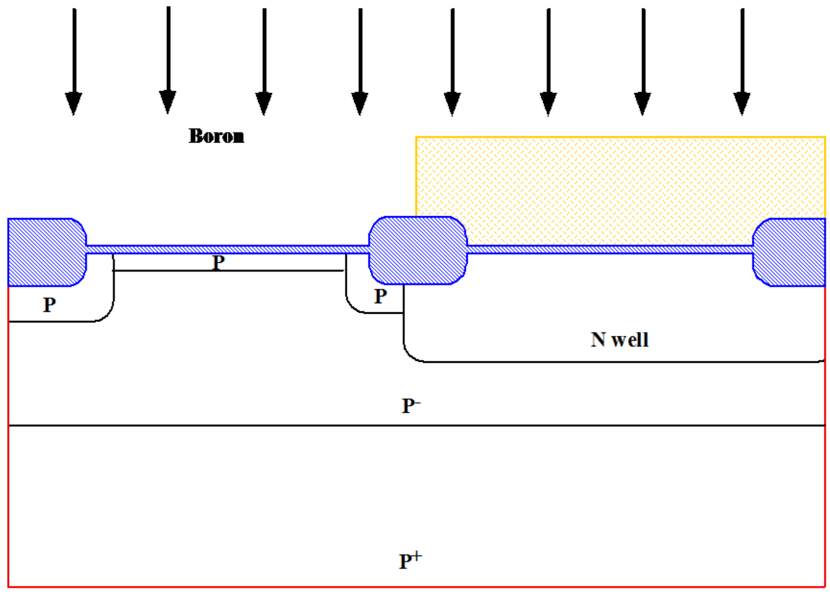
During the LOCOS oxidation, the boron implanted regions diffuse ahead of the growing oxide producing the P doped regions under the field oxide. The Si_3N_4 is stripped after the LOCOS process.



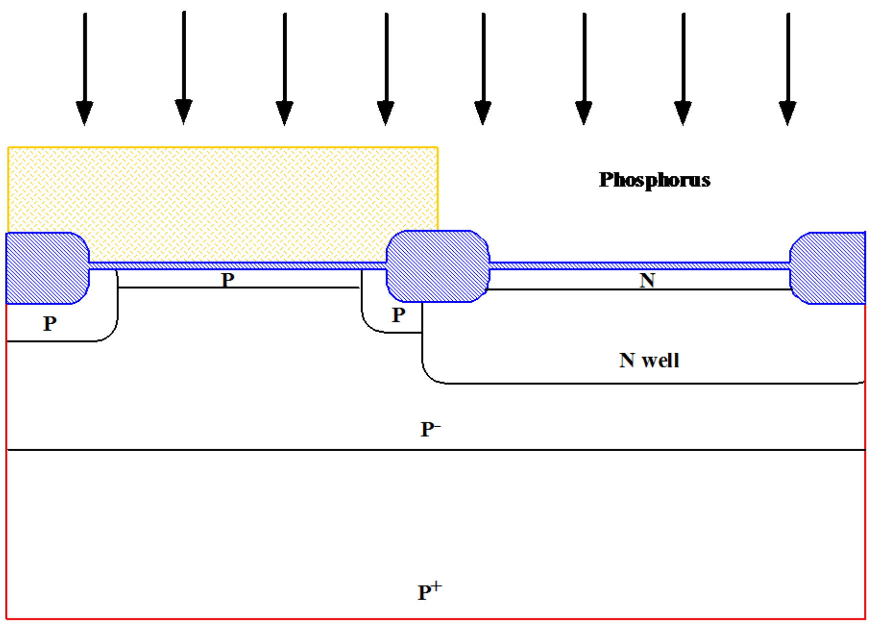
Mask #2 is used to form the N well. Photoresist is used to mask the regions where NMOS devices will be built. A phosphorus implant provides the doping for the N wells for the PMOS devices



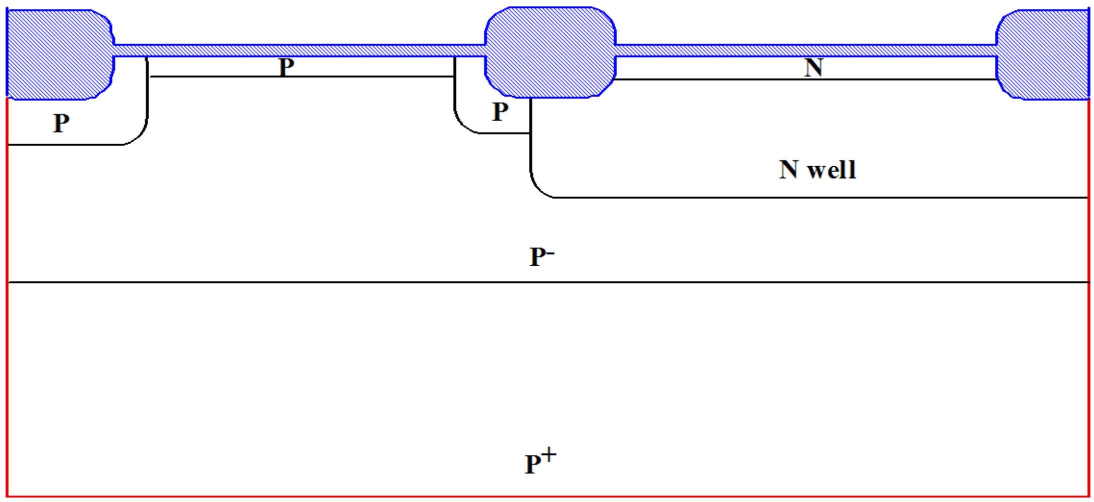
A high temperature drive-in completes the formation of the N well.



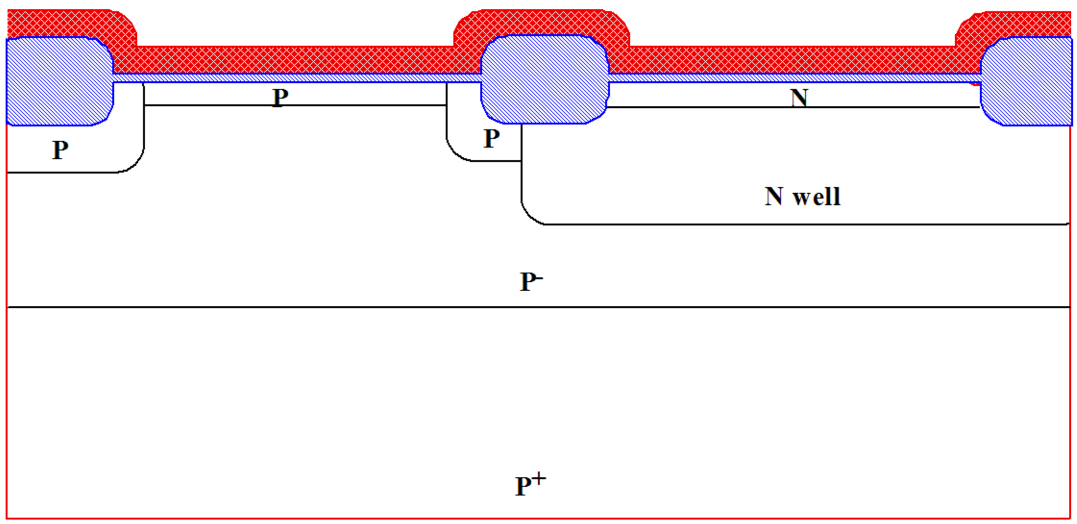
After spinning photoresist on the wafer, mask #3 is used to define the NMOS transistors. A boron implant adjusts the N channel V_{TH}.



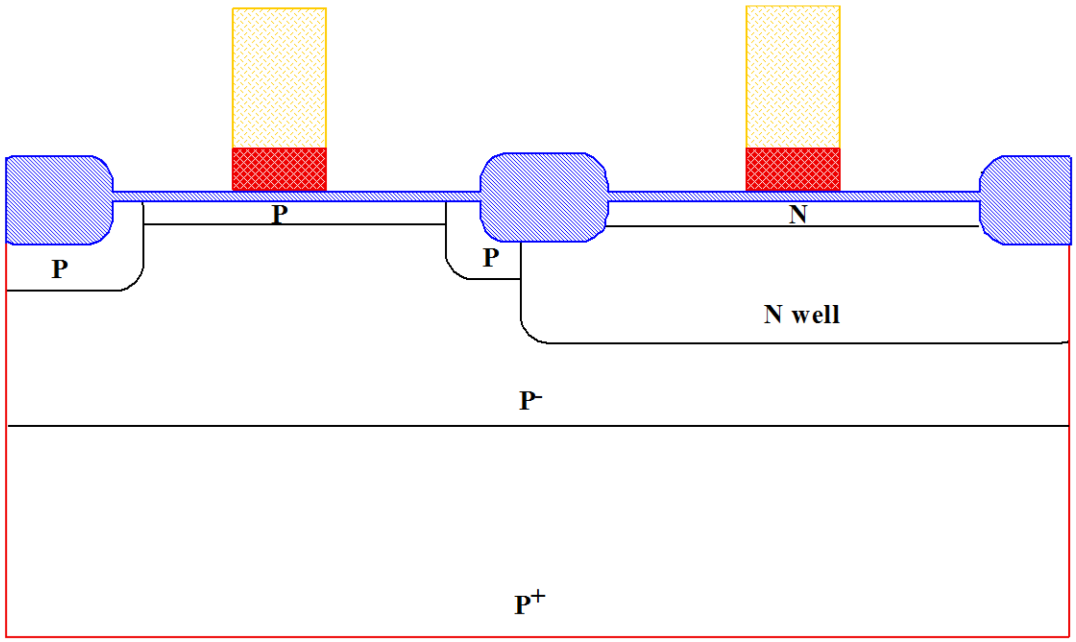
After spinning photoresist on the wafer, mask #4 is used to define the PMOS transistors. A phosphorus or arsenic implant adjusts the P channel V_{TH}. (Depending on the N well doping, a boron implant might actually be needed at this point instead of an N type implant, to obtain the correct threshold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



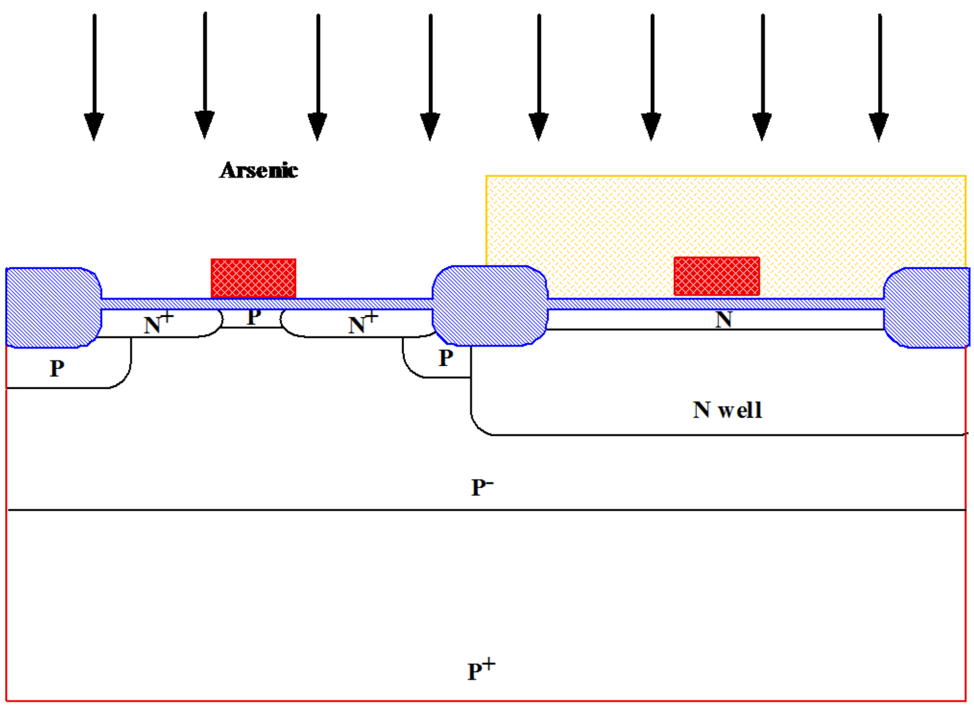
After etching back the thin oxide to bare silicon, the gate oxide is grown for the MOS transistors.



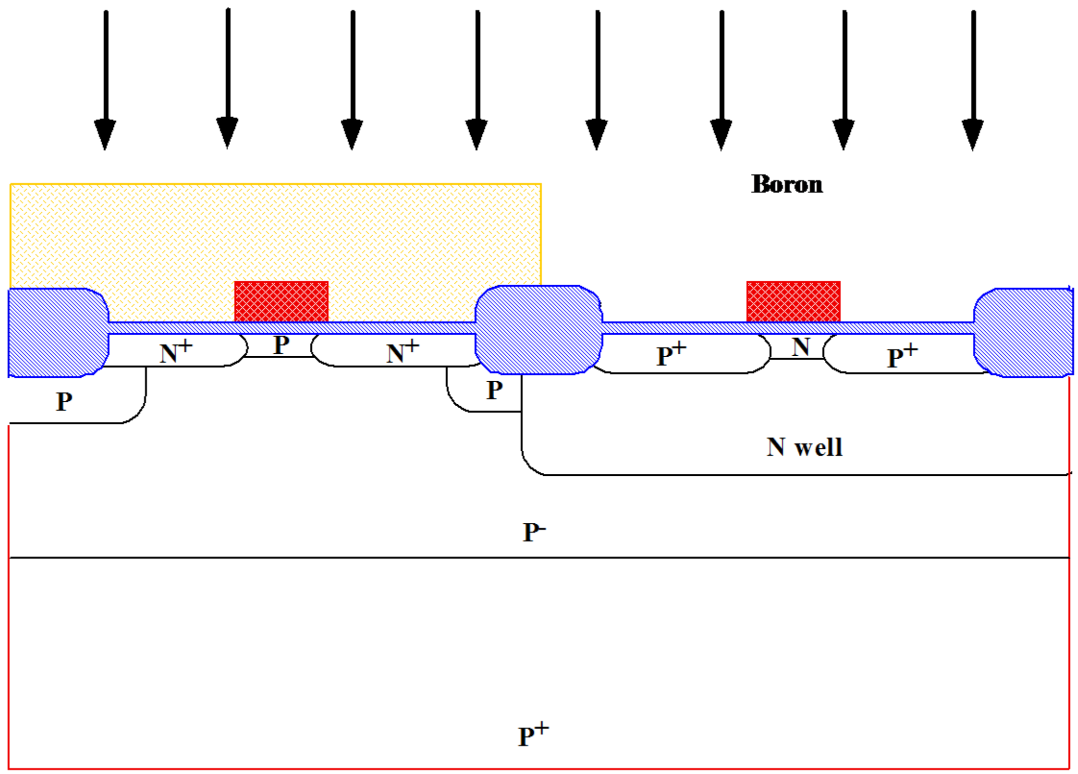
A layer of polysilicon is deposited. Ion implantation of phosphorus follows the deposition to heavily dope the poly.



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.

Problem 2

Answer:

The boron diffusion coefficient is

$$\text{At } 900^\circ\text{C: } D_B^{900} = 1.0\exp\left(-\frac{3.5}{k(900+273)}\right) = 9.27\times10^{-16}\ \text{cm}^2\text{s}^{-1}$$

$$\text{At } 1000^\circ\text{C: } D_B^{1000} = 1.0\exp\left(-\frac{3.5}{k(1000+273)}\right) = 1.41\times10^{-14}\ \text{cm}^2\text{s}^{-1}$$

(a) The predep is performed at 900˚C where the boron solid solubility from solid solubility figure in the diffusion notes is

$$C_S = 1.2\times10^{20}\ \text{cm}^{-3}$$

The dose introduced is then

$$Q = \frac{2C_S}{\sqrt{\pi}}\sqrt{Dt} = \frac{2\left(1.2\times10^{20}\right)}{\sqrt{\pi}}\sqrt{\left(9.27\times10^{-16}\right)\left(20\times60\right)} = 1.43\times10^{14}\ cm^{-2}$$

(b) The implicit assumption we will make is that the drive-in for 30 minutes at 1000˚C is sufficient to make the initial predeposition profile look like a delta-function. We will treat the predep profile as a delta function and calculate the junction based on a one-sided gaussian diffusion near a surface. We can check this assumption now:

$$(Dt)_{900} = 20\times60\times9.27\times10^{-16} = 1.11\times10^{-12} <<$$
$$(Dt)_{1000} = 30\times60\times1.4\times10^{-14} = 2.5\times10^{-11}$$

which shows that the initial predep has a (Dt) product 30 times less than the final drive in. This means that the initial profile looks like a delta-function compared to the final profile and we are justified in treating the final profile as a gaussian.
Then

$$x_j = \sqrt{(4Dt)\ln\left(\frac{Q}{C_B\sqrt{\pi Dt}}\right)} =$$
$$\sqrt{\left(4\times1.41\times10^{-14}\times30\times60\right)\ln\left(\frac{1.43\times10^{14}}{1\times10^{16}\sqrt{\pi\times1.41\times10^{-14}\times30\times60}}\right)}$$
$$= 0.27\times10^{-4}\ cm \quad = \quad 0.27\,\mu m$$

(c) A p-type Gaussian profile with a peak surface concentration of $1.2\times10^{20}\ \mathrm{cm}^{-3}$ has an effective conductivity from Irvin's curve of approximately

$$\bar{\sigma} = \frac{1}{\rho_S\ x_j} = 300\ (\Omega\cdot\mathrm{cm})^{-1}$$

Thus, the sheet resistance of the layer is

$$\rho_S = \frac{1}{300\times0.27\times10^{-4}} = 123.46\ \Omega/\mathit{square}$$

Problem 3

Answer:

(a)

$$Q = \frac{2C_S}{\sqrt{\pi}}\sqrt{Dt} \Rightarrow Q \propto \sqrt{t}$$

$$\therefore 2Q \quad \Rightarrow \quad 4t$$

(b)

$$C(0,t)_{drive-in} = \frac{Q}{\sqrt{\pi D t}} = 0.1 C_S$$

$$Q = \frac{2C_S}{\sqrt{\pi}} \sqrt{(Dt)_{predep}}$$

$$\therefore \quad \frac{2}{\sqrt{\pi}} \frac{\sqrt{(Dt)_{predep}}}{\sqrt{(Dt)_{drive-in}}} = 0.1$$

$$\therefore \quad (Dt)_{drive-in} = \left(\frac{20}{\pi}\right)^2 (Dt)_{predep}$$

Problem 4

Answer:

To reach the same depth,

$$D_B t_2 = D_{As}(t_1 + t_2)$$

Both dopants are diffusing from a finite source, being implanted near the surface, so are characterized by a one-sided gaussian

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

For boron,

$$1\times10^{16} = \frac{10^{14}}{\sqrt{\pi D t}} \exp\left(-\frac{\left(0.5\times10^{-4}\right)^2}{4Dt}\right)$$

Iterating gives

$$D_B t_2 = 9.1\times10^{-11} cm^2$$

If we assume a temperature of 1100˚C for the high temperature well drive in, then

$$D_B^{1100C} = 1.0 \exp\left(-\frac{3.5}{kT}\right) = 1.5\times10^{-13}\ cm^2 s^{-1}$$

so that

$$t_2 = \frac{9.1\times10^{-11}}{1.5\times10^{-13}} = 600\ s$$

At this temperature of 1100˚C,

$$D_{As}^{1100C} = 9.17\exp\left(-\frac{3.99}{8.62\times10^{-5}\times(1100+273)}\right) = 2.1\times10^{-14}\ cm^2 s^{-1}$$

$$D_{As}\left(t_1+t_2\right) = 9.1\times10^{-11} cm^2$$

$$t_1+t_2 = \frac{9.1\times10^{-11}}{2.1\times10^{-14}} = 4.3\times10^3\ s$$

$$t_1 = 4.3\times10^3 s - t_2 = 3.7\times10^3 s$$