Some notes on the process follow. The oxides could be either “grown” oxides achieved by directly oxidizing the substrate silicon. Or, they may be chemical vapor deposited oxides. Interestingly, all but the final oxidation can be eliminated if you use ion implant doping instead of thermal diffusion. Photoresist can be patterned and used as a mask for the n+ and p+ doping. Metal can be evaporated or sputtered.

b. To form an Ohmic contact, the thickness of the space charge must be made as thin as...
1. Oxidize silicon wafer

2. Open oxide for p+ Diffusion (PL1)

3. Diffuse p+

4. Open oxide for n+ Diffusion (PL2)

5. Diffuse n+

6. Open contact windows Over p+ and n+ (PL3)

7. Metallize

8. Pattern metal (PL4)

DONE

Note: PL = Photo-Lithography Step

Figure 2: Process flow for an integrated junction diode
possible (to allow, possibly, for tunneling) and the maximum junction field must be made as high as possible (to assist in getting low-voltage breakdown). Heavy doping (in this case, putting an n+ tub in the contact) accomplishes this.

2. When ever a “doping tub” of one sign of carrier is placed in a semiconductor substrate whose majority carrier is of opposite sign, a space charge develops. Majority charge from one side of the junction diffuses to the opposite side of the junction, where it is trapped on the dopant core atoms - creating ions. The trapped charge is fixed charge, not available for transport. The diffusion process continues until an electric field develops which counters the diffusive tendencies of the mobile carriers. As a field exists in the space charge, there is a potential gradient through it, as shown in the figure below:

![Figure 3: The diode space-charge potential variation in the (a) unbiased, (b) reverse biased and (c) forward biased cases.](image)

There is always charge migration in the semiconductor on either side of the junction as a result of the thermal energy of the mobile carriers. This is shown by the “arrows” of current in the figure. At zero bias, the thermally driven current to the right just equals
the current flowing left: there is no net current. Reverse bias shuts off the current flowing right, leaving a small reverse leakage current flowing left (part (b) of the figure). Forward bias significantly reduces the barrier, creating a large current flow from left to right. The current flowing left is still small and constant. The net result is a large current flow to the right.

But this is not the end of the story. When majority charge reaches the opposite side of the junction, it becomes minority charge, subject to significant recombination with the majority charge which is of opposite sign. The space charge edges are continuously replenished with minority charge. This charge must diffuse away from the space charge boundary, as there are only minimal electric fields to create transport. As the charge moves from the junction boundary, more and more of it recombines, leading to a minority charge density vs position plot as shown below:

Figure 4: Minority charge densities at the space-charge boundaries as a function of position, x.

The excess minority charge at the space charge edge is elevated exponentially with
forward bias (more forward bias, more minority charge gets injected across the space charge layer. The excess charge at the space charge boundary is:

\[ n_p(0) = n'_p0(\exp\left(\frac{qV_d}{kT}\right) - 1) \] (1)

Where \( n_p0 \) is the minority electron density in equilibrium. If you know the substrate doping, you can calculate this using the consistency of the np product in equilibrium. Given the exponential drop-off of mobile minority charge due to recombination, the position-dependent minority electron charge on the p-side of the junction is given by:

\[ n_p(x) = n'_p0(\exp\left(\frac{qV_d}{kT}\right) - 1)(\exp(-\frac{x}{L_n})) \] (2)

In our transport model, we assume the diode current is diffusion limited. That is, the transport is limited by the rate at which minority charge can be evacuated from the space charge boundary by diffusion. Thus, we can get the diode current for electrons by evaluating the diffusion equation at the boundary on the p-side as follows:

\[ I_n = AqD_n \frac{dn'_p(x)}{dx} \bigg|_{x=0} \] (3)

where \( A \) is the area of the junction. This evaluates to:

\[ I_n = \frac{Aqnp0}{L_n}(\exp\left(\frac{qV_d}{kT}\right) - 1) \] (4)

Similarly, for holes:

\[ I_p = \frac{Aqpn0}{L_p}(\exp\left(\frac{qV_d}{kT}\right) - 1) \] (5)

And the total current is given by:

\[ I_t = \frac{Aqnp0}{L_n}(\exp\left(\frac{qV_d}{kT}\right) - 1) + \frac{Aqpn0}{L_p}(\exp\left(\frac{qV_d}{kT}\right) - 1) \] (6)

Which simplifies to:

\[ I_t = I_s(\exp\left(\frac{qV_d}{kT}\right) - 1) \] (7)

With:

\[ I_s = \frac{Aqnp0}{L_n} + \frac{Aqpn0}{L_p} \] (8)

It is interesting to note that This equation holds in reverse bias as well. When the diode is in reverse state, the minority concentrations are suppressed. And the shape of
the minority carrier vs position plot is still the same (exponential) it’s just that it starts low and elevates to its equilibrium state in the bulk. Also, you should realize that as the concentration gradient of minority charge goes to zero in the bulk, the current does not go to zero. Transport switches from diffusion limited to drift limited. That is to say, there are electric fields outside the space charge layer. They are just really tiny. Even though they’re tiny, they can sustain the full current due to the high density of majority charge.

There are two types of capacitance associated with this structure: space charge and diffusion capacitances. Changing the terminal bias by some small voltage \( \Delta V \), makes the space charge shrink or grow depending on the sign of \( \Delta V \). Thus a change in charge is associated with a change in terminal bias. The change in charge is proportional to the change in bias (if \( \Delta V \) is small) and the proportionality constant is the capacitance:

\[
C_{sc} = \frac{A\epsilon_{si}}{x_{sc}}
\]  

(9)

In forward bias, the same thing happens, but a lot of the extra bias is dropped over the parasitic resistances and \( x_{sc} \) kind of “pegs” at the unbiased space charge thickness. But in forward bias, minority charge is also stored at the space charge edge. That minority charge changes in response to the terminal bias as well. And again the proportionality relationship is a capacitance - the diffusion capacitance:

\[
C_{diff} = \frac{I_d\tau}{V_{th}}
\]

where \( \tau \) is the minority carrier lifetime, \( I_d \) is the diode current and \( V_{th} \) is the thermal voltage.

3a. The built in voltage is 0.875 and the space charge thickness is 0.86\( \mu \)m. The capacitance per unit area is 1.17 \( \times 10^{-8} \)Fd/cm\(^2\).

b. The diode current is the same through the whole diode. If the total current is 100\( \mu \)A, the current density is that divided by the diode area: \( J_d = 100 \mu \text{A}/10^{-6} \text{cm}^2 = 100 \text{ A/cm}^2 \). From the formulay:

\[
E = \frac{J_d}{e\mu N}
\]

(11)

Where \( N \) is the local doping density. So on the n-side field (given the data in the problem) is 42 V/cm: really small! On the p-side it’s even less: 0.125V/cm.

c. Since the bulk potentials are the same on either side of \( x_{mj} \), the metallurgical junction, the doping is equal in magnitude (opposite in sign) on either side. We can write the following equation for the separation of the Fermi level from mid-gap:

\[
-0.2\frac{x}{2x_{sc}}
\]

(12)
at \( x=0 \) the Fermi level is at mid gap and the electron and hole concentrations are both \( 1.45 \times 10^{10}/\text{cm}^3 \).
So, if we take the x-origin to be at the metallurgical junction, throughout the space charge layer:

\[ n = n_i \exp \left[ \left( \frac{q}{kT} \right) \left( \frac{-0.2x}{x_{sc}} \right) \right] \]  

(13)

and:

\[ p = n_i \exp \left[ \left( \frac{q}{kT} \right) \left( \frac{0.2x}{x_{sc}} \right) \right] \]  

(14)

The product of \( n \) and \( p \) is still \( n_i^2 \) as the system is in equilibrium.

d. The Fermi level “droop” is given from the formulary as:

\[ \Delta \phi_f = \frac{J_d x_{sc}}{q n \mu} \]  

(15)

where \( n \) is the mobile density considered. Remember, there are two effective Fermi levels (“IMREFs” to consider: one for electrons, the other for holes. So, for a typical current density, all we have to do is find a way to estimate the average number of mobile carriers moving through the space charge at any time. That’s the trick here: how do you estimate? Let’s go through some logical processes to see how this is done. As you can see from 3c above, the mobile density really changes rapidly as you move through the junction. Let’s make a starting guess and say \( n \) is the doping concentration. As stated in class, even under extreme forward bias, the junction space charge reduces to only about 50% of its unbiased value. So if we use the space charge thickness calculated in this exam (problem 1) we can use 0.43 microns as an estimate for the space charge forward bias thickness. Take the 100 A/cm\(^2\) given above as a typical as the typical current density. So for electrons, using this set of assumptions droop will be:

\[ \Delta \phi_f = \frac{100 \times 0.43 \times 10^{-4}}{1.6 \times 10^{-19} \times 10^{16} \times 1500} = 0.002V \]  

(16)

and for holes:

\[ \Delta \phi_f = \frac{100 \times 0.43 \times 10^{-4}}{1.6 \times 10^{-19} \times 10^{19} \times 500} = 1.8 \mu V \]  

(17)

Wow! These are really tiny. Too good to be true. So let’s “challenge” ourselves to come up with a more realistic Maybe but that’s because the mobile densities were too high. Let’s instead, use the minority densities at the space charge edges. As we recall from class discussion, at the space charge edges the minority densities are elevated by:

\[ n_p(0) = n_{po} \exp \left[ \frac{q}{kT} \phi \right] \]  

(18)
\[ p_n(0) = p_{no} \exp \left[ \frac{q}{kT} \phi \right] \]  

Here, \( \phi \) is the separation of the non-equilibrium Fermi level at the space charge edge from the equilibrium level deep in the bulk.

Let us make the (apparently) circular argument that there is no droop. In that case \( \phi \) is \( V_a \). Typical forward bias is a tad bigger than \( \phi_{bi} \). In our case, I’ll take it around the built in voltage (\( V_a \approx 0.8V \) for a “worst case”). Then, \( p_{no} = 5.5 \times 10^{17}/\text{cm}^3 \) and \( n_{po} = 5.5 \times 10^{14}/\text{cm}^3 \). Substituting into equation 15 gives:

\[
\Delta \phi_{fn} = 0.033V \\
\Delta \phi_{fp} = 0.0001V
\]  

These are still small, but bigger than our original estimates.

Rather than claim the argument is “circular”, I’d opt to say it was self consistent. Evaluating the excess minority charge densities at the space charge edges and using these values as the “worst case” transported densities (for the proof) yields very small changes in Fermi level position through the space charge. QED.