This week we’re thinking about dopants, surface states, and interfaces between semiconductors.

1. **Dopants.** We went over some of the numbers for dopants in semiconductors in class.

   a) At sufficiently high doping level, the efficiency of doping decreases. That is, adding an additional dopant doesn’t actually give you an additional carrier. Why do you think this might happen? Using the numbers for phosphorus dopants in silicon, at what average dopant concentration do you think we’ll need to start worrying about this “self-compensation” effect? Give an order of magnitude estimate. The simplest approach gives a significant overestimate – one starts to see compensation effects at considerably lower dopant densities.

   b) What do you think would happen to the hydrogen-like bound states of an electron around a P dopant in Si in a piece of material 1 nm from the surface of a wafer?

2. **Surface states.** For your cultural enrichment, read over the original paper by Bardeen on surface states (downloadable from the course website).

   a) Bardeen asserts that a typical density of localized surface states is something like $10^{12}$ per cm$^2$. Suppose we have an ideal, degenerate 3d Fermi gas in a box of side length $L$. Assume the electrons have a density of $10^{17}$ per cm$^3$, and have the free electron mass. Using the formula for the density of states at the Fermi level, how small a block do we need for the number of surface states to be equal to the number of bulk (usual) single-particle states within $\delta E = (k_B x 1 \text{ K})$ of the Fermi surface? Surface states can effectively trap a fair fraction of the charge that one tries to introduce by doping.

   b) Another way of altering the amount of charge in a semiconductor is the field effect, also known as doping by gating. Suppose we have a “gate” electrode on top of an insulating layer with a relative dielectric constant of $\varepsilon = 3.9$. Suppose that the insulating layer is 100 nm thick. Below the insulating layer is a semiconductor hooked up to a reservoir of charge. Think of this device as a parallel plate capacitor, with one plate being the gate electrode and the other being the semiconductor interface with the insulator. How much positive voltage do we need to apply to the gate electrode to induce an electron density at the semiconductor/dielectric interface $10^{12}$ electrons per cm$^2$?
c) One of the most shocking scandals in physics *ever* came to light in 2002, when it was revealed that J. Hendrik Schon, a researcher at Bell Labs, had faked experimental results on a *massive* scale. The eventual fallout from this was the withdrawal and retraction of a huge number of high profile papers, including 17 in either *Science*, *Nature*, or *Phys. Rev. Lett*. You can read about this mess here: [http://www.lucent.com/news_events/researchreview.html](http://www.lucent.com/news_events/researchreview.html). One part of the (now known to be fake) work involved achieving *huge* gated charge densities in organic semiconductor field-effect structures. This should have been (and was!) a big tip-off. For an Al₂O₃ gate dielectric with a relative dielectric constant of 9, what kind of applied gate electric field would be needed to induce a surface charge density of $2 \times 10^{14}$ cm⁻²? How does that compare with the typical reported breakdown field of that material, $\sim 2 \times 10^{8}$ V/m?

3. **Semiconductor interfaces.** For this exercise, you are going to play around with a couple of of the Java applets I’ve told you about. Go to the page: [http://jas.eng.buffalo.edu/education/pn/pnformation/](http://jas.eng.buffalo.edu/education/pn/pnformation/) and let the applet load. The applet lets you dial in the doping density on either side of a *p*-*n* junction, and shows you what happens when the two semiconductors are brought together. The relative sizes of the depletion regions are computed correctly.

   a) Keep the donor density fixed and vary the density of acceptors. How does the relative depletion width of the two sides vary? How does the Fermi level position vary? Why do you think the depletion width changes depending on the doping level?

   b) Now go to the website: [http://home3.netcarrier.com/%7Echan/SOLIDSTATE/BANDS/bands.html](http://home3.netcarrier.com/%7Echan/SOLIDSTATE/BANDS/bands.html). This applet doesn’t compute depletion widths, but it does allow you to drag around all the energy scales. What condition needs to be fulfilled to get a barrier-like discontinuity in the conduction band?