Written Exam
IH1611 Semiconductor Devices
Tuesday, January 10, 2017, 8-13

Write clearly and draw figures according to the instructions!
Sign your name and personal number on all answer sheets!
Use a new sheet for every task.
Examiner and responsible teacher: Gunnar Malm, 08-790 43 32

The student may use the following items during the exam: Calculator, ruler, and the attached ”Material Properties and Formulas” for the 2016 course round.

Structure: *The exam consists of eight tasks of five points each, total score 40 points. The tasks are given in approximately increasing order of difficulty.*
A pass grade (E) typically requires a score of 20 points. Carefully read and consider all tasks at the start of the exam.

Students who do not pass the exam, and according to the judgment of the examiner are close to the pass limit, will be offered one chance to complement their exam and thereby receive a passing grade (E). No other grades are achievable in this circumstance.

If nothing else is stated in the tasks: Assume that the material is silicon (Si) and room temperature (T=300 K).

Task 1 (5p)

Study Figure 1 below:

a) Characterize each of the materials 1, 2, and 3 as a metal, semiconductor, or an insulator. Use the band structures, to motivate your answers!

b) Which of the three materials is most likely to be transparent for visible light?

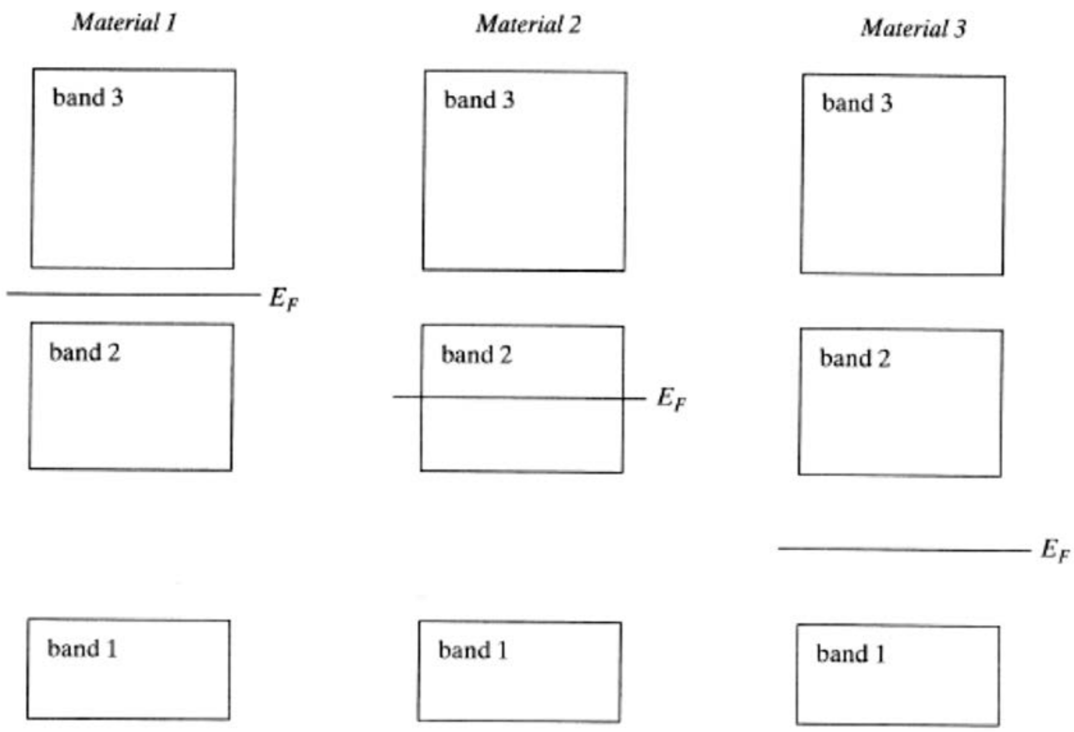


Figure 1. Energy bands of three different materials

Solution

First note that the band structures are actually identical. The difference in between materials 1, 2, and 3 lies in the position of the Fermi level E_F.
The material with the least probability to find carriers in the upper bands (conduction bands) is material 3 since E_F is inside a wide bandgap and the probability to find free carriers decreased fast for higher energy.

Material 2 indicates an approximately half-filled band. This is a property of a metal.
Finally Material 1 has an upper band gap that is small enough so that thermally generated carriers will be available and hence this would be the material with semiconducting properties.

Material 3 is likely transparent to visible and also longer wavelength light such as near IR. High energy light in the UV range would be needed to excite EHP.

Task 2 (5p)

In Complementary MOS (CMOS) technology two types of devices are formed according to the schematic cross-sections in Figure 2. Explain the fabrication/process-steps that are needed, to form these two complementary devices, in the same substrate. Underline at least three keywords in your solution.

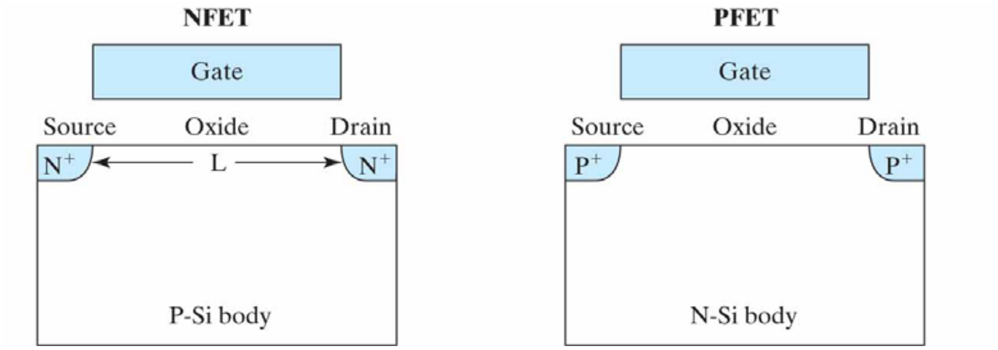


Figure 2. Schematic drawings of N- and P-channel MOSFETs

Solution

First note that the NFET and PFET are **structurally identical.** Remember that they are also commonly referred to as NMOS and PMOS, and that they differ in the carrier type in the so called channel.
The process steps that produce the transistors are found in the category that are called **front-end** process step. In contrast the **back-end** process steps realize the interconnects, that tie the devices together in a complex circuit configuration.

Integrated devices are fabricated on <u>wafers</u> i.e. the substrate that was mentioned above. To be able to fabricate two types of devices, the initial doping polarity and concentration needs to be modified to suitable levels for the NMOS and PMOS threshold voltages respectively. Also very highly doped regions at the source and drain are needed, in order to form low resistive Ohmic contacts.
This is achieved by <u>ion-implantation</u> of the desired dopant species – Boron (B) and Arsenic (As) atoms are implanted into the substrate, with a suitable energy in the keV range and varying dose. Several <u>lithographic mask steps</u> are needed to define the different regions (wells and contact areas).
To dope the substrate high energy is needed while the source/drain junctions are shallow and require low energy. Still, in order to reach ohmic contacts, the dose in that case is rather high. Implanted dopants remain electrically inactive until a thermal treatment i.e. <u>activation</u> at or above 1000 °C is performed to rearrange the partly damaged lattice and place the dopants in electrical active sites (replacing Si atoms in the crystal).

Task 3 (5p)

Derive the current continuity equation for electrons for the following condition. The sample is in steady state (no time derivative) and there is no external generation rate. By continuity it is understood that the carrier number in a given volume is determined by the carrier flow and the recombination rate.

Solution

Study the flow of carriers through a certain volume of semiconductor material.
In steady state, the number of electrons flowing (positive x-direction) into the volume across the boundary with area A is equal to the number (per second) of electrons exiting the volume plus the number of electrons that recombine with holes. It does not really matter if the volume is n-type or p-type. Part of the electrons will recombine in both cases. Now since the current flow is opposite to the electron transport direction we get:

$$A \cdot \frac{J_n\left(x+\Delta x\right)}{q} = A \cdot \frac{J_n\left(x\right)}{q} + A \cdot \Delta x \cdot \frac{n'}{\tau} \tag{1.1}$$

Meaning that electrons enter from the right and fewer electrons exit at the left.

The limit of this expression becomes:

$$\frac{J_n\left(x+\Delta x\right) - J_n\left(x\right)}{\Delta x} = q\frac{n'}{\tau} \tag{1.2}$$

$$\frac{dJ_n}{dx} = q\frac{n'}{\tau} \tag{1.3}$$

Task 4 (5p)

An abrupt Si pn-junction with area 10^{-4} cm^2 has the following properties:

p side	n side
$N_A = 10^{17}\,\text{cm}^{-3}$	$N_D = 10^{15}\,\text{cm}^{-3}$
$\tau_n = 0.1\ \mu\text{s}$	$\tau_p = 10\ \mu\text{s}$
$\mu_p = 200\ \text{cm}^2/\text{Vs}$	$\mu_n = 1300\ \text{cm}^2/\text{Vs}$
$\mu_n = 700\ \text{cm}^2/\text{Vs}$	$\mu_p = 450\ \text{cm}^2/\text{Vs}$

The junction is forward biased by 0.5 V. What is the forward current?
What is the reverse current at a reverse bias of -0.5 V?

Solution

We need the diode equation that can be written in a compact notation according to:

$$I = I_0\left(e^{qV/kT} - 1\right)$$
$$I_0 = Aqn_i^2\left(\frac{D_p}{L_pN_d} + \frac{D_n}{L_nN_a}\right) \quad (1.4)$$

Note that the diffusion constants (and lengths) should be calculated using minority carrier mobility values from the table above!

$$\mu_n = 700 \ \text{cm}^2/\text{Vs}$$
$$\mu_p = 450 \ \text{cm}^2/\text{Vs}$$

Also recall the Einstein relation and how to find the diffusion length:

$$D_{n,p} = \frac{kT}{q}\mu_{n,p} \quad (1.5)$$
$$L_{n,p} = \sqrt{D_{n,p}\tau_{n,p}} \quad (1.6)$$

Numerics step by step give:

$$D_n = 18.1 \ \text{cm}^2/\text{s}$$
$$L_n = 0.0013 \ \text{cm}$$
$$D_p = 11.655 \ \text{cm}^2/\text{s}$$
$$L_p = 0.0108 \ \text{cm}$$

Now evaluate the saturation current to:

$$I_0 = 1.95\times10^{-15} \ \text{A}$$

Under forward bias the exponential term totally dominates so we have

$$I = I_0 e^{qV/kT} = 1.95\times10^{-15} e^{0.5/0.0259} = 4.7\times10^{-7} \ \text{A}$$

The reverse bias condition results in a current that is simply $-I_0$

Task 5 (5p)

What are the approximate thermal velocities of electrons and holes in silicon at T = 400 K? Recall that the average kinetic energy of the free carriers is $\frac{3}{2}kT$.

Solution

Recall the kinetic energy of a particle with mass m

$$E = \frac{mv^2}{2} \tag{1.7}$$

For carriers in a semiconductor we have to use theire effective masses, since they are moving in a periodic potential that is due to the lattice structure.

Electron effective mass	$\mathbf{m_n}$	0.26 m_0
Hole effective mass	$\mathbf{m_p}$	0.39 m_0

Free electron mass	m_0	$9.11\cdot10^{-31}$ kg

Solving for the thermal velocity yields:

$$v_{th} = \sqrt{\frac{3kT}{m_{n,p}}}$$

Inserting values gives:

$$v_{th,n} = 2.6\times10^5 \text{ m/s}$$

$$v_{th,\mathrm{p}} = 2.1\times10^5 \text{ m/s}$$

Task 6 (5p)

An important class of non-volatile memory devices is realized by a floating gate structure, see Figure 3. Explain how the stored charge, in the floating gate, affects the IV-curve of this MOS-type device and how a reading of the memory state can be achieved!

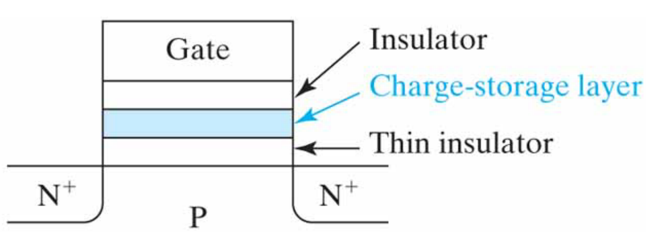
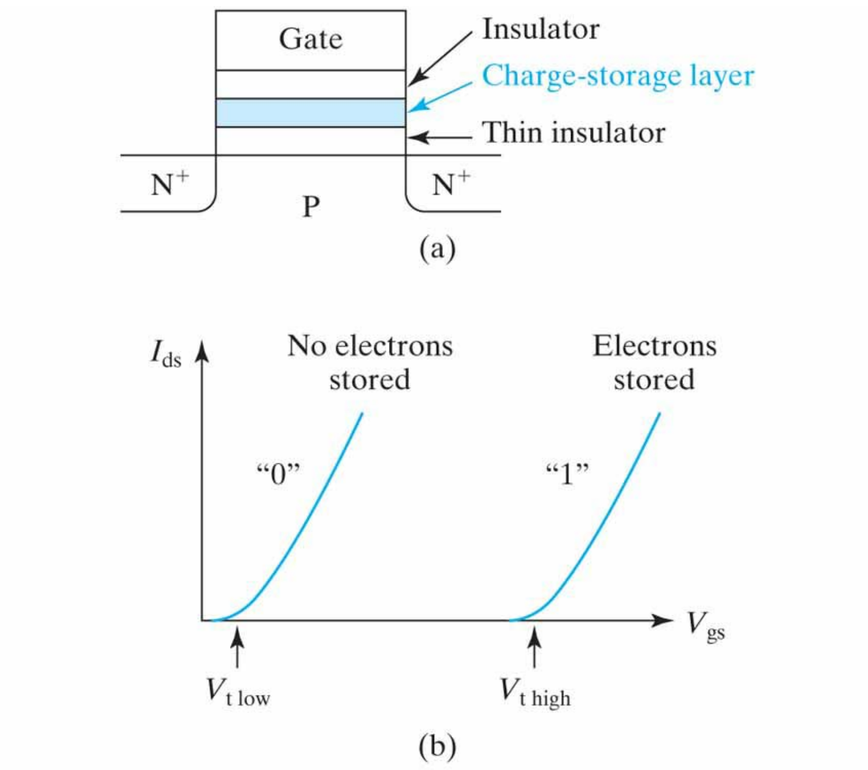


Figure 3. A charge storage nonvolatile memory cell

Solution

Refer to Fig 6-37 (b) in the book that shows that V_t shifts to higher, more positive, values as electrons are stored on the gate. By reading the current in the channel for a certain applied gate voltage the state of the memory can be sensed. Assume for example that the sensing circuit applies a *Vgs*, in between the low and the high threshold voltages. If no current flows then there is charge stored on the gate and vice versa.



Task 7 (5p)

An nMOSFET has a gate oxide stack, with two layers, consisting of:

- 1 nm SiO_2 (closest to the silicon surface)
- 3 nm HfO_2 (on top)

Sketch the energy band diagram for this system! Assume a flatband condition, n-type polysilicon gate, and p-type substrate. It is given that HfO_2 has a band gap of roughly 6 eV, an electron affinity of 2.14 eV, and a relative dielectric constant of 20. For SiO_2 the bandgap is 9 eV, the affinity is 0.95 eV and the relative dielectric constant is 3.9.

Solution

Use the given electron affinities to align the conduction bands, the rest follows. The dielectric constant information is not needed. All the bands should be flat.

Task 8 (5p)

The inverse slope of the subthreshold swing for MOSFETs is denoted by *S*. See Figure 4 for an illustration. Perform a calculation that shows that *S* approaches the value of 60 mV/decade for an optimized device and at T = 300 K. State your assumptions clearly.

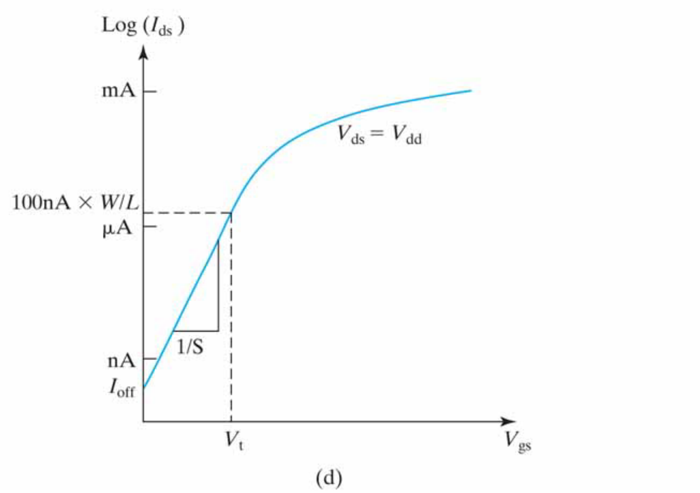


Figure 4. Subthreshold characteristics of a MOSFET device.

Solution

This type of graph has current in log-scale on the y-axis, hence the somewhat unsual unit of “decade”. The slope of the current would be

$$1/S = \frac{\Delta y}{\Delta x} = \frac{\Delta \log(I)}{\Delta V} = \left[\frac{decades}{mV}\right]$$

The subthreshold current of a MOSFET is known to have an exponential voltage dependence on the surface potential:

$$I_{subth} \propto e^{\frac{q\varphi_s}{kT}} \propto e^{\frac{qV_g}{\eta kT}} \tag{1.8}$$

Using the definition of threshold voltage combined with off-state current we the arrive at:

$$I_{off}\left(\text{nA}\right) = 100\frac{W}{L}e^{\frac{-qV_t}{\eta kT}} = 100\frac{W}{L}10^{\frac{-V_t}{S}} \tag{1.9}$$

Assume ideality (η = 1) allows us to solve for *S*:

$$S = kT\ln\left(10\right) = 0.0596 \approx 60 \text{ mV/decade}$$