FINAL EXAM

12 December 2007 **Time allowed: 120 minutes** **80 points total**

NAME: ____________________

STUDENT NUMBER: ____________________

This exam addresses the materials physics involved in three different kinds of semiconductor devices. To receive full credit, you must answer the questions clearly and completely; support your answer with a quantitative relation or formula whenever possible. You have until 11:00 (approximately 120 minutes from now) to complete this test.

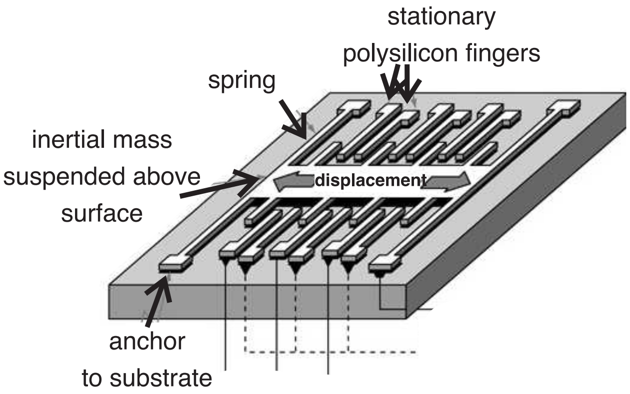
Equations, constants, and semiconductor parameter tables for your use are at the end of this test.

* If you are using your own formula sheet (one 8.5” x 11” piece, both sides, containing ONLY formulae – no figures, diagrams, tables, or annotation), you must hand it in with your exam. *

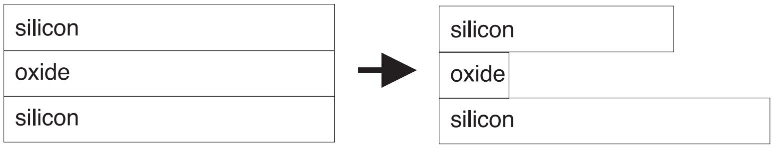
Device I: Accelerometer [20 points total]

The figure below shows an accelerometer. This device is used to deploy airbags in cars.

(a) [4 points] Briefly describe how this device translates a change in acceleration into an electrical signal.



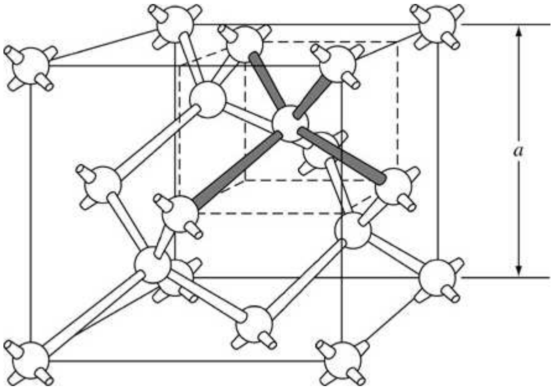
(b) [6 points] Briefly describe the fabrication steps involved to produce the suspended "fingers" of silicon used in an accelerometer. Assume that you start with the silicon-oxide-silicon layers shown below (left) and end up with the suspended silicon piece shown below (right).



Device I: Accelerometer (continued)

(c) [6 points] If an accelerometer can detect capacitance changes larger than 1 nF, and if its sensor "fingers" are 1 μm away from the anchored surface, how far must the finger move to produce a detectable capacitance change? (Assume the accelerometer operates in air.)

(d) [4 points] Most semiconductor-based accelerometers are made from silicon, whose crystal structure is represented below. Given a lattice constant a = 5.43 Å, what is the density of atoms in the (101) plane of silicon?



Device II: Laser pointer [30 points total]

Laser pointers are now widely available because of the development of diode lasers.

(a) [4 points] Many lasers are *pn* junction diodes. Sketch (or give the circuit diagram for) a *pn* junction diode. Indicate *n*-type and *p*-type regions, as well as the direction of current flow required to induce light emission.

(b) [4 points] Determine the required applied voltage to induce a forward-biased diode current of 1.5 mA in a *pn* junction diode at $T = 300$ K. (The reverse saturation current is 1 x 10^{-14} A.)

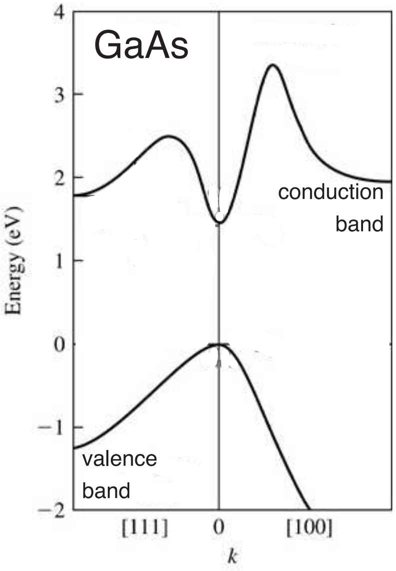
Device II: Laser pointer (continued)

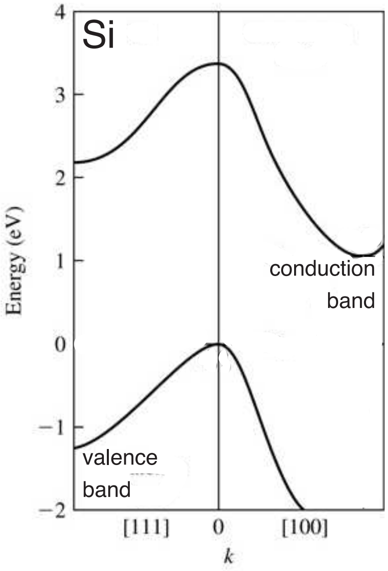
(c) [6 points] Lasing can't occur in all materials. Briefly describe the population inversion condition, including why it leads to lasing and how this condition is met in a diode laser device.

(d) [6 points] List three factors that affect the external quantum efficiency of a light-emitting device, and describe the role that a material's index of refraction has on each of these factors (if applicable).

Device II: Laser pointer (continued)

(e) [4 points] GaAs is widely used as a diode laser material, and its band structure is shown below. Does this diagram have enough information to tell you if GaAs is a material that will allow lasing? Justify your answer.



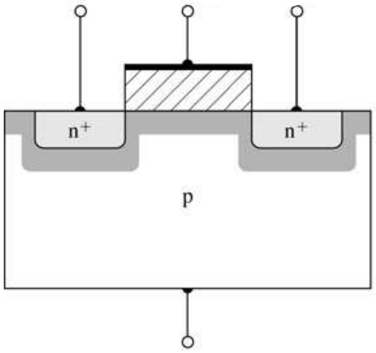


(f) [6 points] GaAs can also be used in quantum dot (or quantum well) lasers. Briefly describe how a quantum well laser is different from a standard diode laser and how this influences the colour of the light emitted from the device.

Device III: An electronic switch [30 points total]

Transistors, including MOSFETs, are devices that can be used to switch on and off current flow between two terminals in an electronic device.

(a) [2 points] A schematic diagram of a MOS device is shown below. Is it NMOS or PMOS? Briefly justify your answer.

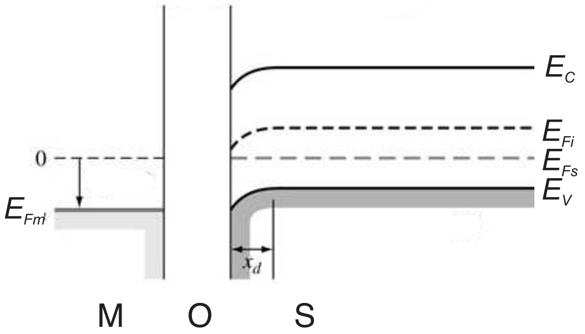


(b) [6 points] On the schematic MOSFET diagram above, label the terminals, and explain why voltages need to be applied between specific terminals to allow the device to function like an on-off switch.

Device III: An electronic switch (continued)

(c) [6 points] MOSFETs are often silicon-based devices. If a Si substrate has $n_0 = 4.5 \times 10^4$ cm^{-3} and $N_a = 5 \times 10^{15}$ cm^{-3} at $T = 300$ K, calculate the position of the Fermi energy with respect to the valence band edge.

(d) [6 points] A schematic diagram of the energy bands for a NMOS device operating in inversion mode is shown below. Describe and indicate on the diagram how the band diagram would change for operation in accumulation mode.



Device III: An electronic switch (continued)

(e) [6 points] Current flow through any semiconductor material is affected by scattering events. Briefly describe two causes of scattering in semiconductors, and give an expression that relates carrier scattering time and a material's electrical conductivity.

(f) [4 points] There are economic incentives for making MOSFETs as small as possible, but these are accompanied by device design challenges. If the thickness of the oxide layer in a MOSFET is decreased by a factor of two, describe how one other device parameter must change to maintain constant-field scaling. Briefly describe why constant-field scaling is useful.

$$E_n = \frac{-m^*e^4}{(4\pi\epsilon)^2 2\hbar^2 n^2} \qquad E = h\nu = \frac{hc}{\lambda} = \frac{\hbar^2 k^2}{2m} \qquad J_n = -ev \qquad g(E) = \frac{4\pi(2m^*)^{3/2}}{h^3}\sqrt{E - E_{bandedge}}$$

$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} \approx \exp\left[\frac{-(E - E_F)}{kT}\right] \qquad N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} \qquad r_n = a_0 n^2 \epsilon_r \left(\frac{m_0}{m^*}\right)$$

$$E_{Fi} - E_{midgap} = \frac{3}{4}kT\ln\left(\frac{m_p^*}{m_n^*}\right) \qquad n_0 = n_i\exp\left[\frac{E_F - E_{Fi}}{kT}\right] = N_c\exp\left[\frac{-(E_c - E_F)}{kT}\right]$$

$$n_d = \frac{N_d}{1 + \frac{1}{g}\exp\left(\frac{E_d - E_F}{kT}\right)} \qquad n_0 p_0 = n_i^2 \qquad \frac{n_d}{n_d + n_0} = \frac{1}{1 + \frac{N_c}{gN_d}\exp\left[\frac{-(E_c - E_d)}{kT}\right]}$$

$$E_c - E_F = kT\ \ln\left(\frac{N_c}{n_0}\right) \qquad n_0 = \frac{(N_d - N_a)}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2} \qquad E_F - E_{Fi} = kT\ \ln\left(\frac{n_0}{n_i}\right)$$

$$J_{drf} = e(\mu_n n + \mu_p p)\varepsilon \qquad v = \frac{eEt}{m_p^*} \qquad \mu = \frac{e\tau}{m^*} \qquad J_{nx|dif} = eD_n\frac{dn}{dx} \qquad \frac{D}{\mu} = \frac{kT}{e}$$

$$R' = \frac{\delta n(t)}{\tau_{n0}} \qquad n = -\frac{I_x B_z}{edV_H} \qquad \mu_n = \frac{I_x L}{enV_x Wd} \qquad V_{bi} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) \qquad \frac{d^2\phi(x)}{dx^2} = \frac{-\rho(x)}{\epsilon_s} = \frac{-\varepsilon(x)}{dx}$$

$$x_n = \left[\frac{2\epsilon_s V_{bi}}{e}\left(\frac{N_a}{N_d}\right)\left(\frac{1}{N_a + N_d}\right)\right]^{1/2} \qquad \varepsilon_{max} = \frac{-2V_{bi}}{W} \qquad C' = \left[\frac{e\epsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)}\right]^{1/2}$$

$$I_D = I_S\left[\exp\left(\frac{V_D}{V_t}\right) - 1\right] \qquad J = \left[\frac{4\pi e m_n^* k^2}{h^3}T^2\exp\left(\frac{-e\phi_{B0}}{kT}\right)\right]\left[\exp\left(\frac{eV_D}{kT}\right) - 1\right]$$

$$T \approx 16\left(\frac{E}{V_0}\right)\left(1 - \frac{E}{V_0}\right)\exp(-2K_2 a) \qquad I_D = K_n(V_{GS} - V_T)^2 \qquad I_D = K_n[2(V_{GS} - V_T)V_{DS} - V_{DS}^2]$$

$$K_n = \frac{W}{L}\frac{\mu_n C_{ox}}{2} \qquad x_{dT} = \left(\frac{4\epsilon_s|\phi_{Fp}|}{eN_a}\right)^{1/2} \qquad \phi_{ms} \equiv \left[\phi'_m - \left(\chi' + \frac{E_g}{2e} + |\phi_{Fp}|\right)\right]$$

$$V_{FB} = \phi_{ms} - \frac{Q'_{ss}}{C_{ox}} \qquad V_{TN} = \frac{|Q'_{SD}(\max)|}{C_{ox}} - \frac{Q'_{ss}}{C_{ox}} + \phi_{ms} + 2|\phi_{Fp}| \qquad \phi_{Fp} = -V_t\ \ln\left(\frac{N_a}{n_i}\right)$$

$$C'_{FB} = \frac{\epsilon_{ox}}{t_{ox} + \left(\frac{\epsilon_{ox}}{\epsilon_s}\right)\sqrt{\left(\frac{kT}{e}\right)\left(\frac{\epsilon_s}{eN_a}\right)}} \qquad C'_{min} = \frac{\epsilon_{ox}}{t_{ox} + \left(\frac{\epsilon_{ox}}{\epsilon_s}\right)x_{dT}} \qquad n_s = N_a\ \exp\left(\frac{\Delta\phi_s}{V_t}\right)$$

$$\Delta L = \sqrt{\frac{2\epsilon_s}{eN_a}}\left[\sqrt{|\phi_{Fp}| + V_{DS}(\text{sat}) + \Delta V_{DS}} - \sqrt{|\phi_{Fp}| + V_{DS}(\text{sat})}\right] \qquad I'_D = \left(\frac{L}{L - \Delta L}\right)I_D$$

$$E_{eff} = \frac{1}{\epsilon_s}\left(|Q'_{SD}(\max)| + \frac{1}{2}Q'_n\right) \qquad \mu_{eff} = \mu_0\left(\frac{E_{eff}}{E_0}\right)^{-1/3} \qquad I_v(x) = I_{v0}\ \exp[-\alpha x] \qquad g' = \frac{\alpha I_v(x)}{h\nu}$$

$$V_{oc} = V_t\ \ln\left(1 + \frac{I_L}{I_S}\right) \qquad P = IV \qquad \eta = \frac{I_m V_m}{P_{in} \times 100\%} \qquad \Gamma_{ph} = \frac{I_L}{eG_L AL} = \frac{\tau_p}{t_n}\left(1 + \frac{\mu_p}{\mu_n}\right) \qquad n_i = \gamma\eta$$

$$\Gamma = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2 \qquad \theta_C = sin^{-1}\left(\frac{n_1}{n_2}\right) \qquad I_\nu = I_\nu(0)\exp[\gamma(\nu)z]$$

Table B.4 | Silicon, gallium arsenide, and germanium properties (T = 300 K)

Property	Si	GaAs	Ge
Atoms (cm^{-3})	5.0×10^{22}	4.42×10^{22}	4.42×10^{22}
Atomic weight	28.09	144.63	72.60
Crystal structure	Diamond	Zincblende	Diamond
Density (g/cm^{-3})	2.33	5.32	5.33
Lattice constant (Å)	5.43	5.65	5.65
Melting point (°C)	1415	1238	937
Dielectric constant	11.7	13.1	16.0
Bandgap energy (eV)	1.12	1.42	0.66
Electron affinity, χ (V)	4.01	4.07	4.13
Effective density of states in conduction band, N_c (cm^{-3})	2.8×10^{19}	4.7×10^{17}	1.04×10^{19}
Effective density of states in valence band, N_v (cm^{-3})	1.04×10^{19}	7.0×10^{18}	6.0×10^{18}
Intrinsic carrier concentration (cm^{-3})	1.5×10^{10}	1.8×10^{6}	2.4×10^{13}
Mobility (cm^2/V-s)			
Electron, μ_n	1350	8500	3900
Hole, μ_p	480	400	1900

Table 3.3 | Impurity ionization energies in silicon and germanium

	Ionization Energy (eV)	
Impurity	**Si**	**Ge**
Donors		
Phosphorus	0.045	0.012
Arsenic	0.05	0.0127
Acceptors		
Boron	0.045	0.0104
Aluminum	0.06	0.0102

Table 3.4 | Impurity ionization energies in gallium arsenide

Impurity	Ionization Energy (eV)
Donors	
Selenium	0.0059
Tellurium	0.0058
Silicon	0.0058
Germanium	0.0061
Acceptors	
Beryllium	0.028
Zinc	0.0307
Cadmium	0.0347
Silicon	0.0345
Germanium	0.0404

Table B.6 | Properties of SiO_2 and Si_3N_4 (T = 300 K)

Property	SiO_2	Si_3N_4
Crystal structure	[Amorphous for most integrated circuit applications]	
Atomic or molecular density (cm^{-3})	2.2×10^{22}	1.48×10^{22}
Density (g-cm^{-3})	2.2	3.4
Energy gap	≈9 eV	4.7 eV
Dielectric constant	3.9	7.5
Melting point (°C)	≈1700	≈1900

$N_A = 6.02 \times 10^{23}$ $\quad k = 1.38 \times 10^{-23}$ J/K $= 8.62 \times 10^{-5}$ eV/K $\quad e = 1.60 \times 10^{-19}$ C

$m_0 = 9.11 \times 10^{-31}$ kg $\quad \epsilon_0 = 8.85 \times 10^{-12}$ F/m $\quad \mu_0 = 4\pi \times 10^{-7}$ H/m

$M = 1.67 \times 10^{-27}$ kg $\quad h = 6.625 \times 10^{-34}$ J·s $= 4.135 \times 10^{-15}$ eV·s $\quad c = 2.998 \times 10^{10}$ cm/s