Team-Based Take-Home Final Exam

Due Monday 12 December 2022 by 11:30 AM

Submit through Gradescope (one submission per team)

Instructions:

1. **Read** the problem statement CAREFULLY!

2. **Identify, formulate, and solve** *all* portions of this complex engineering problem by applying principles of engineering, science, and mathematics.

3. Make sure you address **each constraint** of the problem.

4. Submit a **formal report** to the client for the application.

    a. As detailed below, the report must include a (I) title page, (II) executive summary, and (III) appendix. The appendix should contain the details of your assumptions, designs, calculations, justifications, and design validations. After the title page, include your last names in the header at the top of every page and page numbers in the footer of every page.

    b. The standards of a high-quality professional report are expected: full grammatically correct sentences, clear concise explanations, labeled figures with descriptive captions, proper units for all quantities.

5. To complete this exam, you may use your textbook (*Principles of Electronic Materials and Devices*, S.O. Kasap 3rd or 4th Editions), your class notes, and any resources available through the website site for this course. ***You may not use the general internet or other resources for this exam.***

6. You must **work with your team** but may not collaborate with anyone outside of your team.

7. I am available to answer any questions, and I am willing to provide a review of one draft of your report prior to your final submission.

Problem Statement: Design an Ultrafast Thin Film Photodetector

Your firm has been hired to design a thin film photodetector specific to the output of a pulsed Ti:sapphire laser (800 nm wavelength, 150 fs pulses, 80 MHz repetition rate). Your team has been selected as the project lead with the responsibility to establish the design and select the materials for the photodetector such that it will meet the client's constraints. Once deciding on a detector design, your team evaluates the design and theoretically/computationally validates your selections. As project lead, your deliverable to the client is a typed, professional report consisting of

1. ***Title page (1 page)***
   a. your names, date, MSE 311, and your own title.
2. ***Executive Summary (1-2 pages)***
   a. Problem Statement: A brief summary of the application and constraints.
   b. Proposed Design: A concise description of the proposed detector design.
   c. Design Performance: A brief summary of the key detector properties/metrics referenced to how they meet the client's constraints. If you cannot simultaneously meet all constraints, discuss the tradeoffs and any recommendations.
3. ***Appendix (10 page limit)***
   a. Include all necessary, relevant, and labeled figures, plots, tables, and calculations used to support your design and materials selection.
   b. Include at least one clear, detailed, to-scale schematic of the proposed detector design.
   c. Include a fully labeled to-scale energy versus position figure (i.e., a band diagram in eV vs. microns). Any band bending can be sketched but should be approximately correct. Label the Fermi energy, the space charge layer, the conduction and valence band(s), work functions, electron affinities, etc.
   d. Include the calculations for each application requirement and/or constraint.
   e. For the metal electrodes, include an evaluation of cost, environmental impact, toxicity, and sustainability.
   f. Assume 3 significant figures and include proper units.

Client's Application Requirements and Constraints

- Your client has provided the following rigid design constraints for the application.
- You must meet these constraints, *if possible*, based on the materials available at your firm (firm resources described below). If you cannot meet all constraints, propose a solution.
- Any assumptions must be documented and justified.

Ultrafast Thin Film Photodetector

a. Detect photons of 800 nm in wavelength at an incident power of 1.00 nW.

b. Operate at 300 K.

c. Cross-sectional area of 10.0 μm × 10.0 μm for the detector illuminated surface.

d. Bias of up to 5.00 V can be applied to the detector in either polarity.

e. Maximum dark current of 10.0 fA.

f. Under illumination, differential current (ΔI) of 10.0 μA minimum and 500 μA maximum.

g. Maximum overall detector thickness of 20.0 μm.

h. Illuminated surface
   i. Conductive electrode material over entire detector cross-sectional area (defined in c).
   ii. Transparent: maximum incident intensity loss of 10.0%.
   iii. Thickness: 100 nm minimum to 500 nm maximum, subject to transparency constraint.

i. Detection region
   i. One or more intrinsic or doped semiconducting materials.
   ii. Thickness: 500 nm minimum to 20.00 μm maximum.
   iii. Maximum average *electron* transit time of 20 picoseconds across depletion region, or maximum average *electron* transit time of 200 picoseconds across entire semiconducting region.
   iv. Maximum thermal power of 100 pW delivered by absorbed photons.
   v. Absorb >90.0% of all photons incident on the detection region.

j. Back surface
   i. Material with high thermal conductivity ($\geq$ 100 W $m^{-}1$ K^{-1}) and high electrical conductivity ($\geq 10^5$ Ω^{-1} cm^{-1}).
   ii. Ohmic contact to semiconducting detection region.
   iii. Thickness: 1.00 μm minimum to 5.00 μm maximum.

k. Global, economic, environmental, and social context constraints
   i. Selection of the metals used for the electrodes should include an evaluation of costs, environmental impact, toxicity, and sustainability.
   ii. If performance constraints cannot be met with the lowest cost, lowest environmental impact, lowest toxicity, and highest sustainability, discuss which physical features or performance metrics could be modified.

Resources: You are restricted to the following materials available at your firm

I. Conductive Electrode Materials

Material	Magnesium (Mg)	Indium Tin Oxide (ITO)	Cadmium Stannate (Cd_2SnO_4)	Aluminum Zinc Oxide (AZO)	Gold (Au)
Work function (eV)	3.66	4.50	4.92	5.02	5.10
Optical absorption coefficient @ 800 nm (cm^{-1})	1205500	891	6450	1500	770890
Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	150	10.0	5.63	1.19	315
Resistivity (nΩ m)	43.9	4000	1300	10000	20.5
Conductivity ($\Omega^{-1}\ cm^{-1}$)	227790	2500	7692	1000	487805
Abundance (% by lowest element)	2.33	0.000025	0.000015	0.07	0.0000004
Cost (by highest cost element, $/g)	3.00	2.52	2.40	0.88	89.67
Toxicity (exposure limit, mg/m3)	Not toxic	Possibly	0.005	5	n/a
Ecological (LC50 animal, mg/L)	n/a	Aquatic chronic	9.38	n/a	n/a

II. Semiconducting Materials

Material	Germanium (Ge)	Silicon (Si)	Gallium Arsenide (GaAs)
Band gap (eV)	0.66	1.12	1.42
Electron affinity (eV)	4.0	4.05	4.07
Effective density of states in conduction band, N_C (cm^{-3})	1.04×10^{19}	2.8×10^{19}	4.4×10^{17}
Effective density of states in valence band, N_V (cm^{-3})	6.0×10^{18}	1.2×10^{19}	7.7×10^{18}
Intrinsic carrier concentration (cm^{-3})	2.3×10^{13}	1.0×10^{10}	2.1×10^{6}
Electron drift mobility (μ_e) ($cm^2\ V^{-1}\ s^{-1}$)	3900	1400	8800
Hole drift mobility (μ_h) ($cm^2\ V^{-1}\ s^{-1}$)	1900	450	400
Conduction band electron effective mass, $\frac{m_e^*}{m_e}$	0.56	1.08	0.067
Valence band hole effective mass, $\frac{m_h^*}{m_e}$	0.40	0.60	0.50
Dielectric constant (ε_r)	16.0	11.9	13.0
Optical absorption coefficient @ 800 nm (cm^{-1})	50608	1027.9	13455
Thermal conductivity ($W\ cm^{-1}\ °C^{-1}$)	0.6	1.5	0.46
Indirect minority carrier lifetime (s) (τ_h in n-type or τ_e in p-type)	$\tau \approx \frac{5\times10^{-7}}{\left(1+2\times10^{-17} N_{\text{dopant}}\right)}$		--
Direct recombination capture coefficient, B ($m^3\ s^{-1}$)	--	--	7.21×10^{-16}
Effective Richardson constant, B_e ($A\ cm^{-2}\ K^{-2}$)	67	110	8

Your firm has bulk wafers of these semiconductors at various doping levels and can deposit thin films of these with controlled doping levels.

If you need material properties not found in the table above or in your textbook, please let me know.