Student first and last name: | Sciper:

EPFL - MICRO-301 – Manufacturing technologies – Final Exam 2021

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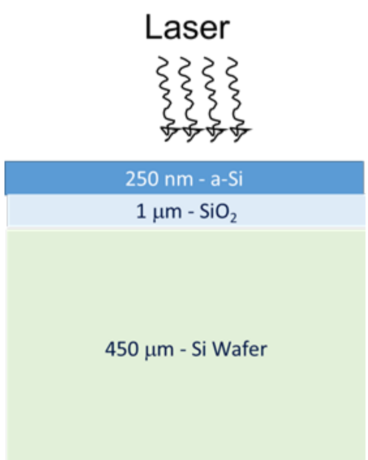
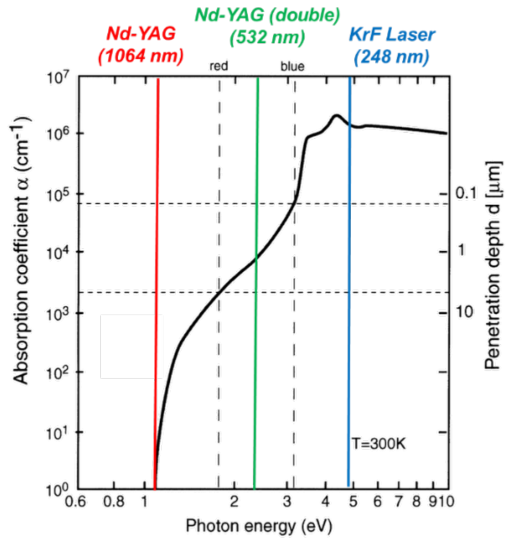
Part I / Small exercises

Laser manufacturing

Modern TFT-Displays are often based on amorphous silicon and use temperature-sensitive substrates. Our process objective is to anneal an amorphous silicon layer (a-Si) deposited on top of a SiO_2 itself on a Si substrate to crystallize it (see schematic below). The laser should only heat the top layers, while preserving the layers beneath it. The absorption curve for Si (graph is adapted from a work from G. de Graaf et al. TU Delft). We assume that the amorphous phase of Silicon (a-Si) follows the same absorption behavior. The wavelength for three different industrial lasers are added.





1. What should the criteria for choosing the wavelength, the pulse duration and pulse energy? (check all the statements that are correct. Note that there is a penalty when you select an incorrect statement)

   - ☐ *The pulse should be sufficiently long for heating up the a-Si to its annealing temperature, i.e. longer than the electron-matrix recombination time (typ. > ns).*
   - ☐ *The pulse should be sufficiently long for heating up the a-Si to its annealing temperature (typ. > ns), but still short enough so that the heat does not propagate significantly beyond the a-Si layer.*
   - ☐ *The penetration depth should be as small as possible.*
   - ☐ *The penetration depth should be more than the thickness of the a-Si layer.*
   - ☐ *The laser beam spot should be large enough to reduce the thermal gradient and prevent stress formation.*
   - ☐ *The laser beam spot should be small enough, so more efficient heat transfer occurs.*
   - ☐ *The pulse duration should be ultra-short (~ picoseconds or less) and the wavelength of the laser should be such that the laser is not absorbed by the upper layer in order to trigger non-linear absorption.*
   - ☐ *Instead of using pulses, I would turn the laser in continuous emission mode so that the upper-layer is heated for enough long to anneal.*

2. Based on this qualitative assessment, which among the three proposed laser sources would you choose for this task? (The three lasers are capable of producing short pulses of similar duration.) Select one:

   - ☐ *Krypton-Fluoride UV laser - KrF (248 nm)*
   - ☐ *Neodyme-YAG laser (Nd-YAG / 1064 nm)*
   - ☐ *Neodyme-YAG laser (Nd-YAG / 532 nm)*

Conventional machining versus die-sinking EDM

*The task is to **drill** sequentially 12 holes, each of 10 mm in diameter out of a 20-mm thick metal plate. The purpose of the exercise is to compare for various materials the time required to do the processing using two different manufacturing methods. (For simplification, we will assume that the travelling time from one hole to another is negligible compared to the rest of the processing time.)*

	Feed rate	***Spindle speed***	***Surface speed***	***Specific energy***	***Melting temperature***
	(mm/rev)	*(rpm)*	*(m/min)*	*W-s/mm³*	*(°C)*
Aluminum alloys	*0.3*	*1900*	*9500*	*0.75*	*600*
Stainless steels	*0.18*	*375*	*1875*	*4.1*	*1500*
Titanium alloys	*0.15*	*325*	*1625*	*3.55*	*1600*

3. What is the time needed for conventional machining of aluminum? (expressed in s) Answer
4. Same question but for stainless steel. (expressed in s.) Answer
5. Same question but for titanium. (expressed in s.) Answer

6. We consider to case where we would perform the operation using die-sinking EDM. The material remove rate in this case can be empirically found with this formula: $MRR = C \times (T_m)^a \times I$

   Where **C** is a constant (4.10^4), **a** is another constant (-1.23), $\mathbf{T_m}$ the melting point of the material and **I** the applied current. We assume that I = 40 A. Calculate how long it would take to drill the twelve holes by die-sinking EDM in aluminum. (Express the result in s.) Answer

7. Same question than before, but for titanium. (Answer should be given in s.) Answer
8. How does die-sinking EDM compare with conventional drilling? Check (all) the statement(s) that are correct. (Penalties apply when incorrect statements are selected.)

   ☐ *It is more than seventy times slower for aluminum*
   ☐ *It is comparable for titanium*
   ☐ *It is about forty times slower for titanium*
   ☐ *It is about twenty time slower for titanium*
   ☐ *It is about five times faster for aluminum*

9. We recall that for conventional processing, the power required for a give machining is simply the product of the specific energy times the material removal rate. For EDM, we assume that the voltage applied on the electrodes is 20 V. The EDM generator emits pulses of energy with a duty cycle of 10%. How does the ratio of energy consumption between die-sinking EDM and conventional machining compare in these particular cases? (You could calculate for titanium and aluminum to get a range for comparison.)

   Select one:

   ☐ *It is more than twenty times higher*
   ☐ *It is about the same*
   ☐ *It is actually less than conventional machining by a factor two*
   ☐ *It is roughly between 7 and 11 times more*
   ☐ *It is about hundred times higher*

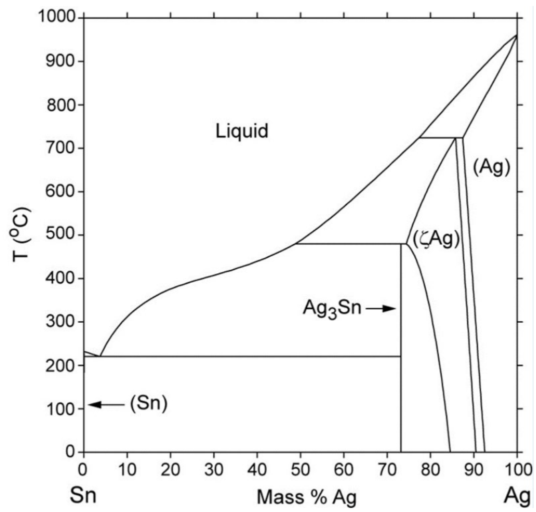
Part II / Study of soldering processes

10. Ag-Sn solders have become very important in electronics and have replaced Pb-Sn solders in many applications. Why?

Select one:

- ☐ *Pb is toxic and its use is banned in many applications*
- ☐ *Ag-Sn is cheaper than Pb-Sn*
- ☐ *Pb is heavier than Ag, so for lightweight consumer applications, a lighter solder is preferred*
- ☐ *Ag-Sn has a lower melting point than Pb-Sn at its respective eutectic point*

11. Consider the phase diagram for Ag-Sn shown below.



What is the eutectic composition of Ag-Sn (HINT, the atomic mass of Sn and Ag are approximately 119 and 108 respectively)? (Select one)

- ☐ *Sn3.8Ag96.2*
- ☐ *Sn73Ag27*
- ☐ *Sn96.2Ag3.8*
- ☐ *Sn10Ag90*

12. What is the solidification temperature (in degrees Celcius) at the Eutectic composition? (select one)

- ☐ *480*
- ☐ *231*
- ☐ *221*
- ☐ *200*

13. Unfortunately, this solder has an instability when placed on copper pads. What is the cause of this instability? (select one)

- ☐ *Cu dissolution*
- ☐ *Oxidation of the solder*
- ☐ *Poor adhesion of Ag on Cu*
- ☐ *Cracking due to thermal expansion coefficient mismatch*

14. SAC solders are generally replacing Sn-Ag solders in many applications. Why? (select one)

- ☐ *Less Cu dissolution*
- ☐ *Less toxicity*
- ☐ *Simpler phase diagram*

15. Consider the cooling of a Sn-Ag solder consisting of 70mass% Sn. At 500C, what phases are present? (select one)

- ☐ *Liquid with 50mass%Sn and 50mass%Ag*
- ☐ *Liquid Sn with solid Sn-Ag with 50% mass of each component*
- ☐ *Liquid with 70mass%Sn and 30mass%Ag*

16. At what temperature do we see the onset of solidification? (select one)

- ☐ *Approximately 300C*
- ☐ *Approximately 400C*
- ☐ *Approximately 220C*

17. At 300C, what phases are present? (select one)

- ☐ *Liquid with 90mass%Sn and solid Ag3Sn*
- ☐ *Liquid with 70mass%Sn and solid Ag3Sn*
- ☐ *Liquid with 70mass%Sn*

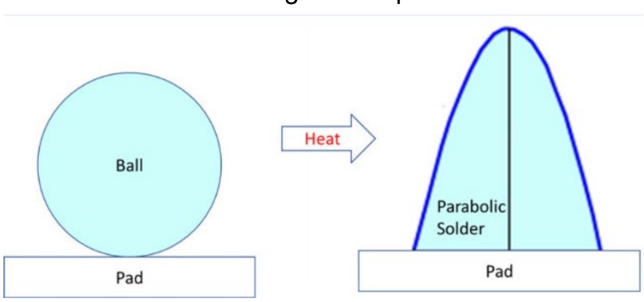
18. When the temperature is lowered below the eutectic temperature, what happens to the liquid? (select one)

- ☐ *It solidifies to form Sn and Ag3Sn*
- ☐ *It solidifies to form a single phase of Sn-Ag with 70mass%Sn*
- ☐ *It solidifies to form Sn and Ag*

19. Sn-Ag solders are commonly used in flip chip applications, where a ball of solder is placed between the chip and the PCB. Consider a chip with 50 μm square pads and 25 μm space between adjacent pad edges. Assuming that pads can only be placed along the edges of the chip, and assuming that no pad can be closer than 25 μm from the edge of the chip, what is the maximum number of pads that a 475 μm on a side square chip can accommodate?

Answer

20. In some applications, the solder is melted after ball deposition to ensure a good connection to the pad. Assume we start with 50 μm solder balls, and, upon melting and solidification, the solder forms a parabola that exactly contacts the edge of the pads.



For convenience, use 2D analysis and assume that the area of the spherical ball and that of the final parabola are the same to conserve mass. What is the height of the resulting parabola (HINT: Area of a circle is πr^2 and area of a parabola is 0.66*ab, where a is the height of the parabola and b is the length of the base chord)?

Answer

21. During packaging, pressure is applied on the chip, which causes the solder balls to compress. Why is this pressure used? (select one)

- ☐ *To ensure that proper contacts are made even if the chip has some non-planarity*
- ☐ *To cause the solder to melt due to the resulting friction*
- ☐ *To ensure that laterally adjacent pads are shorted to each other by solder spreading*

22. During the pressure application, assume the parabola spreads and can grow to a maximum base chord of 70μm without risk of short circuits to adjacent pads. Make the following assumptions:

- Area of the parabola is conserved
- Good contact is made when the parabola just touches the pad on the top

Answer

What is the maximum amount of allowed non-planarity in the chip, in micrometers?

Part III / Carabiners and snap hooks

Carabiners (in French 'mousquetons') and snap hooks are used in various situations, from outdoor sport activities (climbing, caving, etc.) to elevated construction, from multi-purpose hooks to logistics, etc.

The purpose of this exercise is to discuss how carabiners and snap hooks are made.

Design a) ***Design b)*** ***Design c)***

Figure 1. *Various designs and implementations of carabiners and snap hooks. a) A metal carabiner (source Petzl), b) A plastic carabiner (source Dhgate.com) and c) A metal snap-hook (source Aliexpress.com)*

From now on, we will use the term 'snap hook' as a generic term that also includes carabiners.

Functional analysis

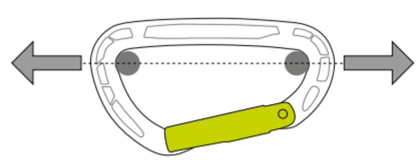
23. Which one among the following sentences provides a generic but accurate definition of a snap hook? In this question, we use the term 'snap hook' as a generic term (which also includes specific design like carabiners). (select one)

- ☐ *A D-shaped metal frame to reversibly link two elements together*
- ☐ *An oblong metal ring that links two ropes together*
- ☐ *A metal loop with a spring-loaded gate to quickly and reversibly connect components, most notably in safety-critical systems.*
- ☐ *A generally oblong shape used to attach a rope to a piton or to connect two ropes*
- ☐ *A closed hook used to secure through a gate, that can open and close, two elements together*

24. What are the *two* key design properties that an engineer would want to optimize when designing a carabiner? (select one)

- ☐ *Weight and thermal conductivity*
- ☐ *Shape and diameter*
- ☐ *Force and elasticity*
- ☐ *Weight and elasticity*
- ☐ *Force capacity and weight*

25. The figure on the left (source: Edelride) illustrates the normal loading conditions of a carabiner, such that most of the load is carried in tension through the spine. To simplify, we assume that the load is equivalent to a *pure* tension applied a rode of diameter D.



- Express the two relevant equations defining the key design properties identified in the previous question.
- Combine these two equations and isolate material properties from design parameters.
- The ratio of these material properties defines *the material performance index*.

This material performance index is: (select one)

☐ $\frac{E}{\rho}$ ☐ $\frac{E^{1/2}}{\rho}$ ☐ $\frac{\sigma_f}{\rho}$ ☐ $\frac{\sigma_f^{\,2}}{E}$

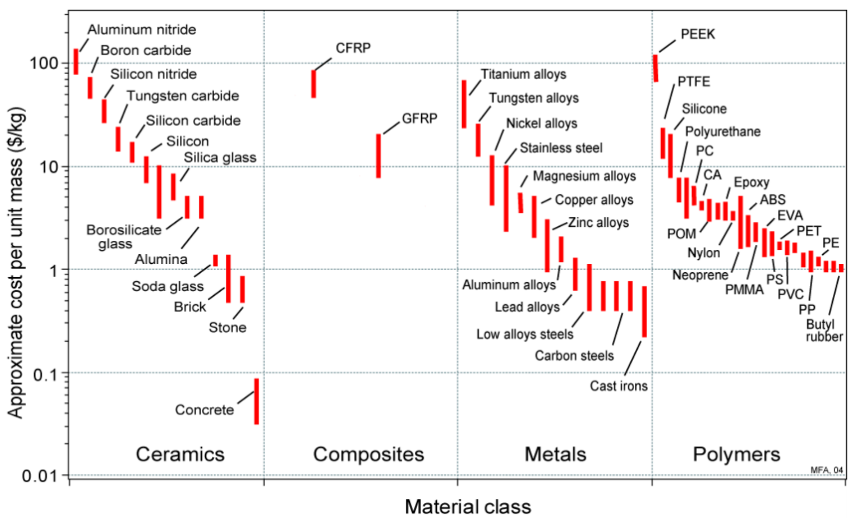
26. Which among the three graphs (related to material physical properties) is relevant to your design optimization problem? *(note: Ashby plots are provided in annex.)*

- ☐ *Strength-Density graph*
- ☐ *Young's modulus-density graph*
- ☐ *Modulus-strength graph*

27. For climbing, safety norms imposed that the material does not break for a normal tension load of 20 kN. Assuming the case of a rod of circular cross-section D = 13 mm, and a material performance index of 100, name three metals that could be possible candidates. Use the selected Ashby plot to make your choice. *Select three metals:*

- ☐ *Magnesium alloys*
- ☐ *Steel*
- ☐ *Copper alloys*
- ☐ *Tungsten alloys*
- ☐ *Lead alloys*
- ☐ *Titanium alloys*
- ☐ *Zinc alloys*
- ☐ *Aluminum alloys*

28. The graph below shows the approximate cost per unit mass for various materials. (source M. Ashby.)



Which one among the metal candidates would have the highest material performance index over price ratio? (select one)

- ☐ *Steel*
- ☐ *Magnesium alloys*
- ☐ *Titanium alloys*
- ☐ *Copper alloys*
- ☐ *Lead alloys*
- ☐ *Tungsten alloys*
- ☐ *Aluminum alloys*
- ☐ *Zinc alloys*

29. Based on the Ashby graph and considering this specific application, have you identified a *non-metal* material candidate that would have higher performances than a metal one for this application? (select one)

- ☐ *There is none*
- ☐ *Carbon Fiber Reinforced Polymer (CFRP)*
- ☐ *Glass Fiber Reinforced Polymer (GFRP)*
- ☐ *Tungsten Carbide (WC)*
- ☐ *Silicone elastomers*
- ☐ *PEEK*
- ☐ *Wood (// grains)*
- ☐ *Polyester*
- ☐ *Silicon Nitride (Si_3N_4)*

30. What would be the advantage of using a non-metal material? Select one or more: (penalties apply for improper choice(s))

- ☐ *Lighter*
- ☐ *Less stiff*
- ☐ *Stiffer*
- ☐ *Stronger*
- ☐ *Cheaper*
- ☐ *None*

Review of manufacturing process

31. We focus our attention on **design a**. We only consider the main part (in orange). What do you think is/are the most likely used manufacturing method(s) among the list provided below? (there can be a combination of processes) (Penalties apply for improper choice(s).)

- ☐ *Electro Discharge Machining*
- ☐ *Forging*
- ☐ *Anodizing*
- ☐ *Painting*
- ☐ *Water-jet cutting*
- ☐ *Metal forming*
- ☐ *Injection molding*
- ☐ *Laser cutting*

32. We now consider **design b**. Same question than before. Choose what you consider is/are the most likely used manufacturing process(es). (Penalties apply for improper choice(s).)

- ☐ *Polishing*
- ☐ *Conventional machining*
- ☐ *Laser ablation*
- ☐ *Forming*
- ☐ *3D printing*
- ☐ *Painting*
- ☐ *Injection molding*

33. Finally, we consider **design c**. Same question than the previous one. (Penalties apply for improper choice(s).)

- ☐ *Laser cutting*
- ☐ *Metal injection molding*
- ☐ *Metal Injection Molding*
- ☐ *Wire electro-discharge machining (EDM)*
- ☐ *Conventional machining*
- ☐ *Water-jet cutting*

34. Assuming that you are producing relatively small amount of a given design of snap hook. Which among the three designs would offer production methods with the highest level of flexibility to rapidly adapt to design variants?

- ☐ *The production method(s) used for design a)*
- ☐ *The production method(s) used for design b)*
- ☐ *The production method(s) used for design c)*

35. We discuss *comparatively* the production economics between the three designs. In this question and in the following one, we now consider the full products (and not just their main pieces). Which one has the lowest bill of materials?

- ☐ *Design a)*
- ☐ *Design b)*
- ☐ *Design c)*

36. Which among the three design, could be produced in the largest quantities for the lowest cost?

- ☐ *Design a)*
- ☐ *Design b)*
- ☐ *Design c)*

Study of variants

37. Consider the variant of **design a)** shown on the right (image credit Petzl).

What could be the *main* purpose of this variant compared to its parent design? (select one)

- ☐ *To decrease the rigidity*
- ☐ *To simplify the manufacturing*
- ☐ *To reduce the weight*
- ☐ *To increase the maximum strength*
- ☐ *To make it more beautiful*

38. 'This variant requires a different manufacturing procedure than its parent design.'

- ☐ *True*
- ☐ *False*

39. We now consider a variant of design c as shown on the right (credit: Aliexpress.com).

What would be the main purpose for this variant? (select one)

- ☐ *To simplify the manufacturing*
- ☐ *To decrease the rigidity*
- ☐ *To protect the flexible element*
- ☐ *To make the design more beautiful*
- ☐ *To reduce the weight*

40. 'This variant requires a different manufacturing procedure than its parent design.'

- ☐ *True*
- ☐ *False*

Manufacturing costs

41. We consider the design a) discussed in the previous section, for which we would like to estimate the manufacturing cost for the main element (in orange color on the picture). To simplify, we consider only one of the production step, the one that bears most of the cost for this product (for which we assume a single given machine cost and tooling). Further, we estimate that each carabiner starts from a cylindrical rod of material of finite length. To estimate the cost per part, we provide the following data:

Cost of raw material	2.75	CHF/kg
Fraction of lost material	0.1	
Volumic mass	2700	kg/m3
Length of the rod	10	cm
Diameter of the rod	12	mm
Rate production	30	parts / min
Fraction of machine time used	90%	
Machine capital investment	100000	CHF
Overhead rate	30	CHF /hr
Pay-back time	10	Years
Cost tooling	20000	CHF
Production size	250000	parts
Production level/tool	30000	parts

What is the production cost for a single part? Answer

42. If we would like to reduce the cost, what would you propose as the *most* impactful thing to work on? (select one)

- ☐ *I would double the production rate*
- ☐ *I would double the production level for a single tool*
- ☐ *I would reduce the tooling cost by a factor two*
- ☐ *I would look for a twice cheaper production equipment*
- ☐ *I would double the production size*

43. Among the set of propositions below, which one would have the smallest impact on the production cost?

- ☐ *Reducing the tooling cost by a factor two*
- ☐ *Doubling the production size*
- ☐ *Investing in a twice cheaper production equipment*
- ☐ *Doubling the production rate*

44. Raw materials prices fluctuate over time for various reasons including scarcity of resources, supply chains issues, speculation or geopolitics. For the material in this application, the cost have been fluctuating by typically +/- 25 % over the last 10 years, which is relatively significant. What would be the impact of such level of cost variations on the carabiner production cost considered here?

- ☐ *Above 20%*
- ☐ *Between 10% and 20%*
- ☐ *Between 5% and 10%*
- ☐ *Between 2% and 5%*
- ☐ *Less than 2%*

END OF THE QUESTIONS

Annex: Ashby plots