

# Erasmus an der Université Grenoble Alpes – Frankreich

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# Wer ich bin und worüber ich berichte

- 23 Jahre alt
- Physik-Student an der TUM
- AEP-Master (3. Fachsemester)
  
- Motivation und Vorbereitung
- Universität und Studium
- Leben und Wohnen
- Bilder



# Motivation und Vorbereitung

- Motivation:
  - Französisch; Süd-Frankreich und die französischen Alpen; Unikurse
- Semesterzeiten
  - September – Januar und Februar – Juni/Juli
- Sprachkenntnisse
  - Französisch ist sehr hilfreich!
  - Sprachkurse werden an der Uni angeboten
- Tipps bei Ankunft
  - Koordinatoren persönlich treffen



# Universität und Studium

## • Lehrangebot (meine Kurse):

- Nanophotonics & Plasmonics
- Quantum Nanoelectronics
- Quantum Engineering
- Physics of Nanostructures

## • Unterrichtsweise:

- Teilweise etwas verschulter
- Viel Tafelanschrift

## • Forschungsmöglichkeiten:

- Research Internship

**Biaxial strain model: 2.b. Fully strained nanostructures**

Lattice mismatch  $f = \frac{\Delta a}{a_s} = \frac{a_e - a_s}{a_s} = 10^{-1} - 10^{-2}$

Model: Free surface along Oz, In plane Biaxial stress  $\sigma$

Crystal under large biaxial stress:  $\sigma \approx 10^{10} \times 10^2 \text{ Pa} \sim 10 \text{ to } 100 \text{ kbar}$

Distortion along the growth axis and the symmetry of the distorted unit cell have to be calculated

Elastic energy has to be calculated  $\Rightarrow$  Elastic relaxation (Oodts) / Plastic relaxation (dislocations)

**Biaxial strain model: 2.b. Fully strained nanostructures**

Specific case of cubic crystals

$$C_{\text{cubic}} = \begin{pmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{pmatrix}$$

3 independent coefficients

[h,k,l] = [001]:  $\epsilon_{11} = \epsilon_{22} = \epsilon_1, \epsilon_{33} = \epsilon_3, \epsilon_{12} = \epsilon_{21} = \epsilon_{13} = \epsilon_{31} = \epsilon_{23} = \epsilon_{32} = 0$

[h,k,l] = [111]:  $\epsilon_{11} = \epsilon_{22} = \epsilon_{33} = \epsilon_1, \epsilon_{12} = \epsilon_{21} = \epsilon_{13} = \epsilon_{31} = \epsilon_{23} = \epsilon_{32} = \epsilon_2$

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**Biaxial strain model: 2.b. Fully strained nanostructures**

Biaxial strain geometry for fully strained nanostructures

$$\epsilon_{11} = 2\epsilon_{xx}, \epsilon_{22} = 2\epsilon_{yy}, \epsilon_{33} = \epsilon_z$$

$$-\frac{2\nu}{1-\nu} \epsilon_{xx} = R \epsilon_{yy}$$

In-plane deformation  $\epsilon_{ij} = \frac{a_{\text{substrate}} - a_{\text{layer}}}{a_{\text{substrate}}}$  fixed by the lattice mismatch

Free surface along Oz, Out-of-plane stress  $\sigma_{33} = 0$

In-plane biaxial stress  $\sigma_{ij}$

Valid for any substrate orientation

$$\sigma_{ij} = Y \epsilon_{ij} \quad \text{with} \quad Y = \frac{E}{1-\nu}$$

Biaxial modulus

$$\epsilon_{\perp} = -R \epsilon_{\parallel} \quad \text{with} \quad R = \frac{2\nu}{1-\nu}$$

Relaxation constant

Elastic energy:  $U = Y \epsilon_{\parallel}^2 S h$

$$= \sqrt{\frac{2\nu}{1-\nu}} \sigma_{\parallel} \epsilon_{\parallel} S h$$

**Biaxial strain model: 2.b. Fully strained nanostructures**

Specific case of cubic crystals: growth along [001] direction

[001] Cubic crystal  $\epsilon = \begin{pmatrix} \epsilon_{xx} & 0 & 0 \\ 0 & \epsilon_{yy} & 0 \\ 0 & 0 & \epsilon_{zz} \end{pmatrix}$

Elastic energy  $U = Y[001] \epsilon_{\parallel}^2 S h$

For fully strained layer:

$$\epsilon_{\perp} = -R[001] \epsilon_{\parallel}$$

Relaxation constant  $R[001] = \frac{2C_{12}}{C_{11}}$

Biaxial modulus  $Y[001] = C_{11} + C_{12} - \frac{2C_{12}^2}{C_{11}}$

More complicated expressions for growth axis // to [hkl]

**Subject #2: Critical thickness induced by formation of interface misfit dislocations**

We consider an epilayer made of a semiconductor A grown on top of an infinitely thick substrate B. The lattice mismatch  $f_{AB}$  is noted  $f$ . The lateral size along  $O_x$  and  $O_y$  is noted  $L$  (see Figure). The epilayer thickness is noted  $h$ . The Young modulus and the Poisson's coefficients are noted  $E$  and  $\nu$ . We use cartesian coordinates ( $O_x, O_y, O_z$ ).

We assume that a regular array of interface misfit dislocations (extra or missing atomic plane in the layer A) is present at the interface with the substrate. The number of dislocations is noted  $N_x$  and  $N_y$  along  $O_x$  and  $O_y$  (see Figure). We assume that each dislocation adds or removes one atomic plane in the top layer A respect to the substrate A. At first order, a dislocation reduces or increases the in-plane length of the layer A by a quantity  $a_0 = a_s$  (lattice parameter of the layer A). We assume also that the local distortion of the lattice around each dislocation leads to an elastic energy per unit length  $E_{MD}$  ( $J.m^{-1}$ ) for each dislocation.

Regular 2D array of interface misfit dislocations (MD)

Epilayer A grown on top of an infinitely thick substrate B. Above a certain thickness  $h_c$ , a 2D array of interface misfit dislocations are formed at the interface between A and B.

Due to the presence of dislocations, the in-plane strain components of the layer A are reduced. The epilayer A is said partially relaxed. We note  $\epsilon_{xx} = \epsilon_{yy} = \epsilon_{\parallel}$  ( $|\epsilon_{\parallel}| < f$ ).

- Using the results given in the course, justify that the elastic energy associated to the volumic elastic strain is given by  $U_{\text{el}} = Y L^2 h \epsilon_{\parallel}^2$  with  $Y = E/(1-\nu)$ .
- Justify that the elastic energy of the misfit dislocations is  $U_{\text{MD}} = N_x L E_{\text{MD}} + N_y L E_{\text{MD}}$ .
- Justify that the dislocation array leads to a reduced value of  $\epsilon_{\parallel}$  given by  $|\epsilon_{\parallel}| = |f| - (a_0/L) N_y$ . Conclude that the total elastic energy is given by  $U_{\text{el}} = U_{\text{vol}} + U_{\text{MD}} - Y L^2 h \epsilon_{\parallel}^2 + 2 |f| a_0 E_{\text{MD}} a_s$ .
- Show that the configuration which minimizes the total energy corresponds to  $h_c = E_{\text{MD}}/(a_s Y)$ .

5. By using that  $\epsilon_{ij}$  is necessary smaller than  $|f|$ , show that the array of dislocation starts only if  $h$  is larger than  $h_c = E_{\text{MD}}/(a_s Y) = Y/f$ .

6. For  $h > h_c$ , conclude that  $\epsilon_{\parallel} = |f| h_c/h$ .

7. Application: the critical thickness of InAs on GaAs is  $h_c = 1.5 \text{ nm}$ . We give  $a_{\text{GaAs}} = 0.35653 \text{ nm}$ ,  $a_{\text{InAs}} = 0.35653 \text{ nm}$ . Calculate the critical thickness of an epilayer In<sub>x</sub>Ga<sub>1-x</sub>As on GaAs.

**Subject #3: Epitaxy of GaSb on GaAs substrate**

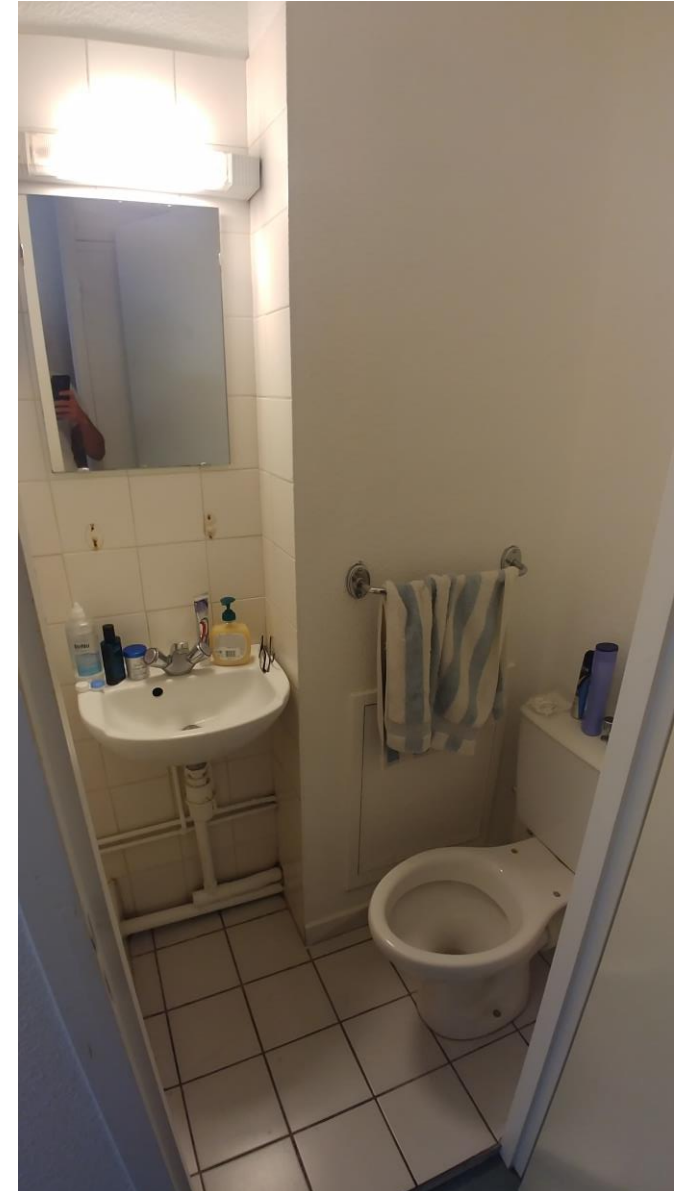
You will find hereafter selected parts (text and figures) extracted from 2 articles published in 2006 in the journal "Applied Physics Letters" about the epitaxy of GaSb on GaAs. GaAs and GaSb owns to the III-V semiconductors having a cubic crystalline structure. Try to answer the following questions:

- Calculate of lattice mismatch between GaAs substrate and GaSb layer. Comment about the epitaxy of this system.
- Describe the strain state of the GaSb layer as function of the monolayer (ML) number and give scientific proofs to argue about this situation.
- Explain the origin of the formula describing the strain energy density  $E_{\text{el}}$  and prove the formula of coefficient B given in the paper. Prove that the coefficient B is also equal to the formula  $B = C_{11} + C_{12} - \frac{2C_{12}^2}{C_{11}}$  for GaSb.
- Explain the origin of the formula describing the dislocation energy density dissipated from a 2D misfit array  $E_{\text{el}}^*$ . Find an error in the formula of  $E_{\text{el}}^*$ . Why the authors use the symbol  $\epsilon_{\parallel}$  in the formula of  $E_{\text{el}}^*$ ?
- (If you have time) Calculate the numerical values of  $E_{\text{el}}$  and  $E_{\text{el}}^*$  (for  $E_{\text{el}}$  calculation take into account the error mentioned in the question 4) and check their values given in the indicate that the misfit dislocation array dissipates the majority 98.5% of strain energy.

GaAs		GaSb	
$E_{\text{GaAs}}$	143 eV	$E_{\text{GaSb}}$	5.73 eV
$\nu$	0.28	$\nu$	0.28
$C_{11}$	119.78 (GPa)	$C_{11}$	88.42 (GPa)
$C_{12}$	53.78 (GPa)	$C_{12}$	40.28 (GPa)

# Leben und Wohnen

- Wohnung:
  - Unterstützung der Uni
  - Studentenwerk-Wohnheime
  - Residence Ouest: eigenes Bad, eigener Kühlschrank, Gemeinschaftsküchen
- Sport- und Freizeitangebot:
  - Uni-Sport
  - Berge und Natur
  - Outdoor-Community
  - Innenstadt
- Corona-Situation



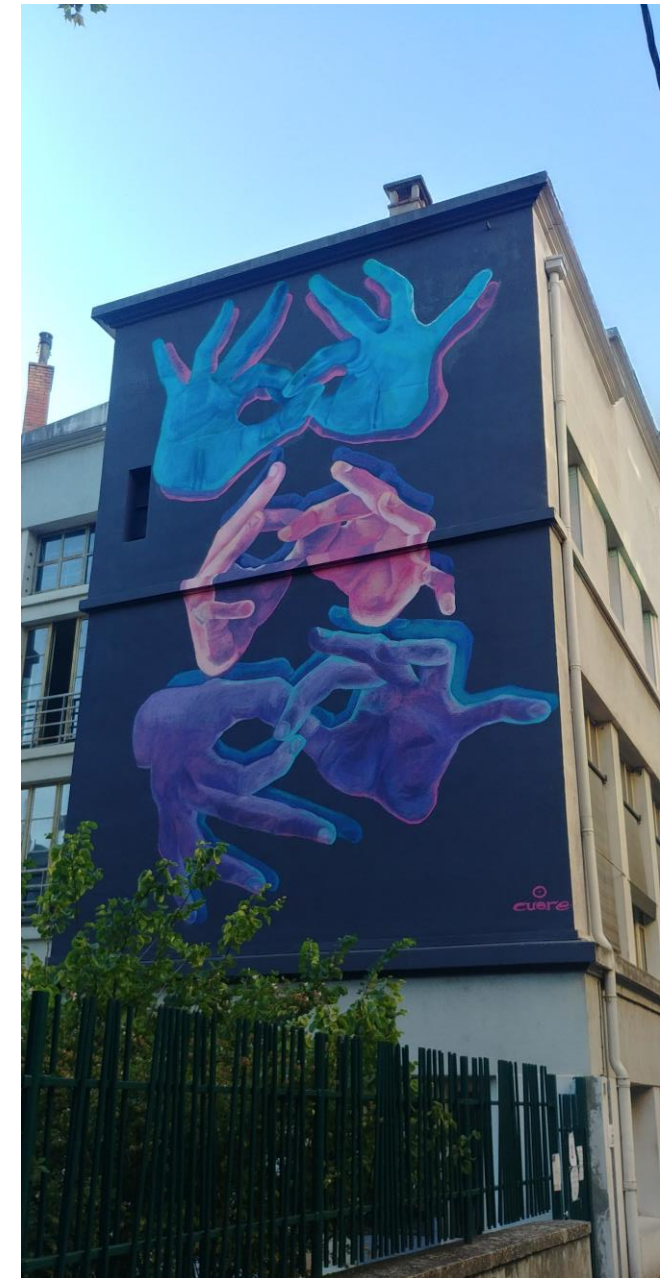


# Bilder und Eindrücke



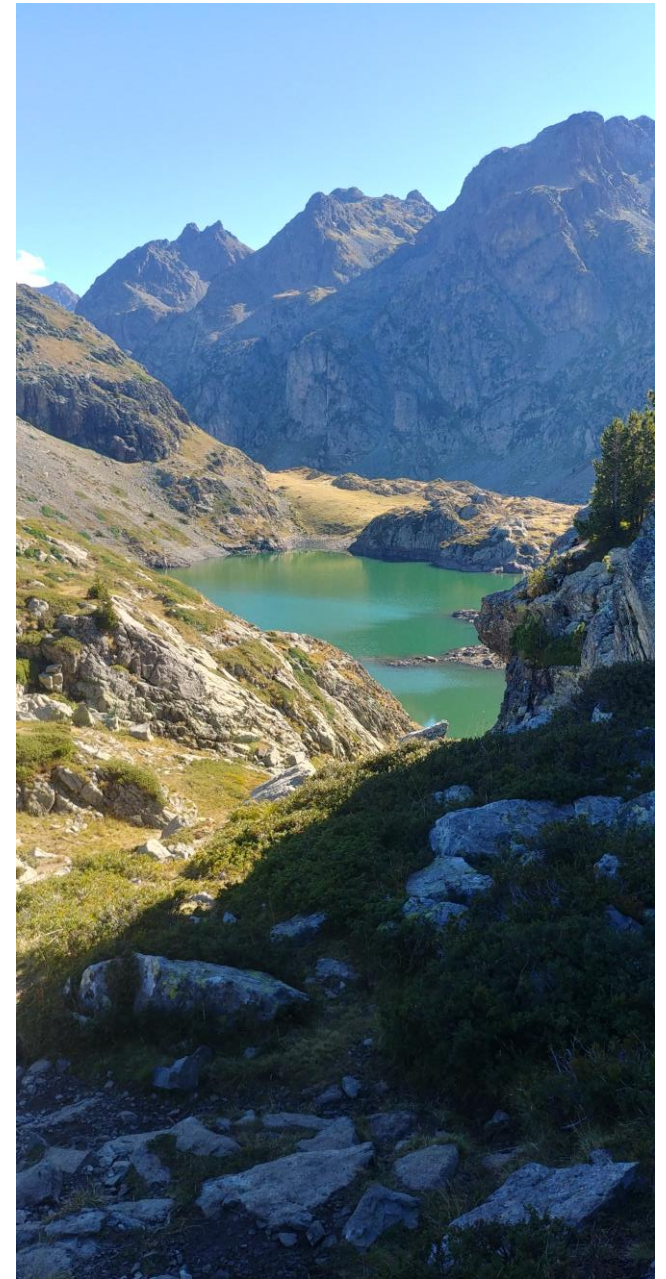


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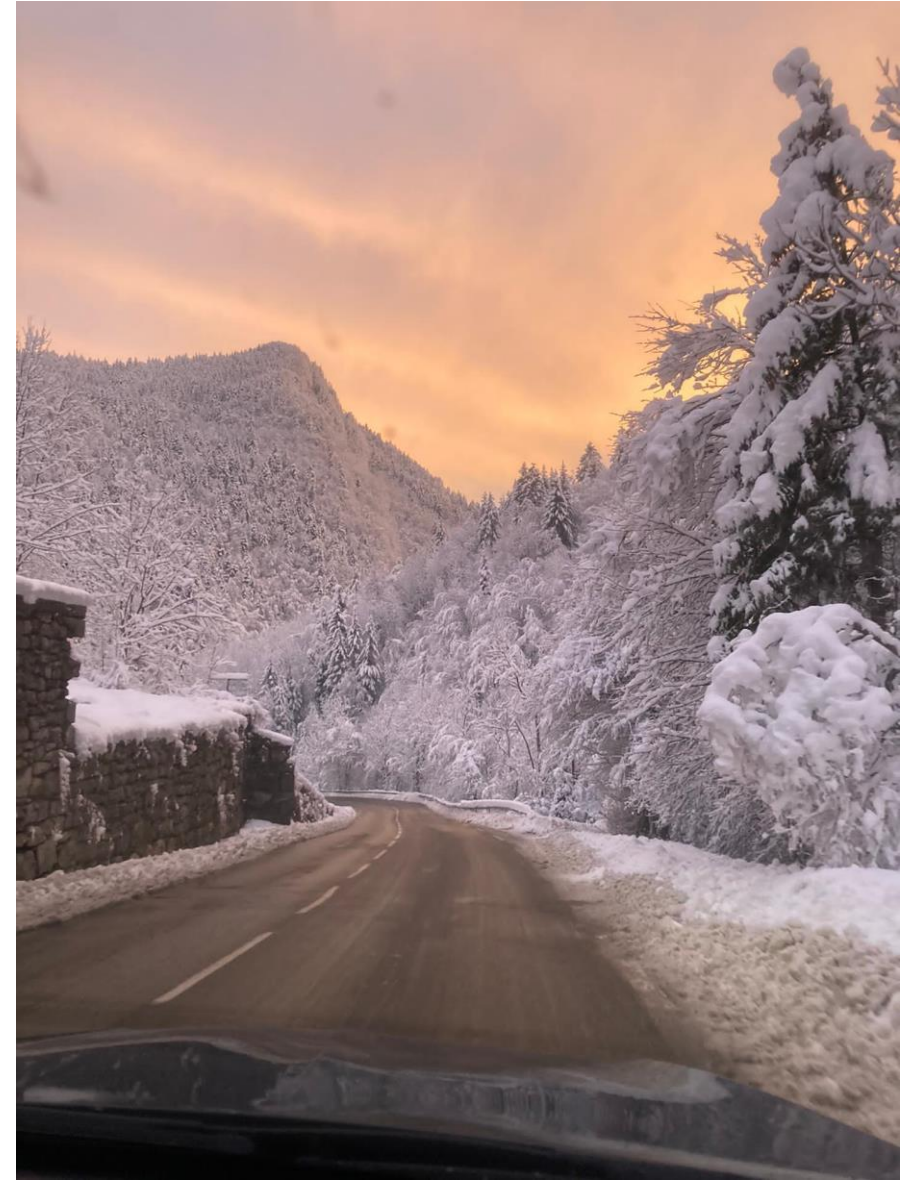


# Bilder und Eindrücke





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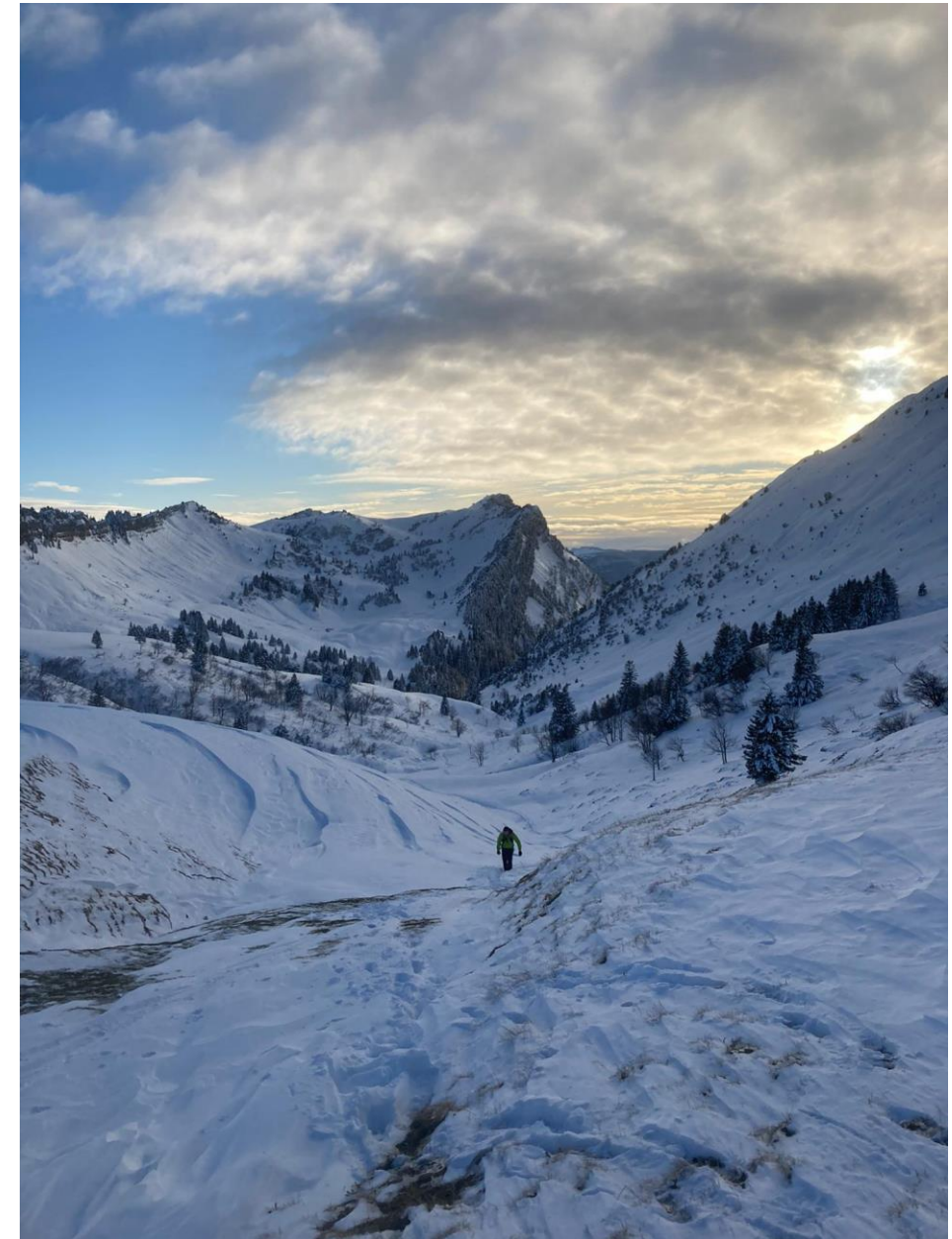


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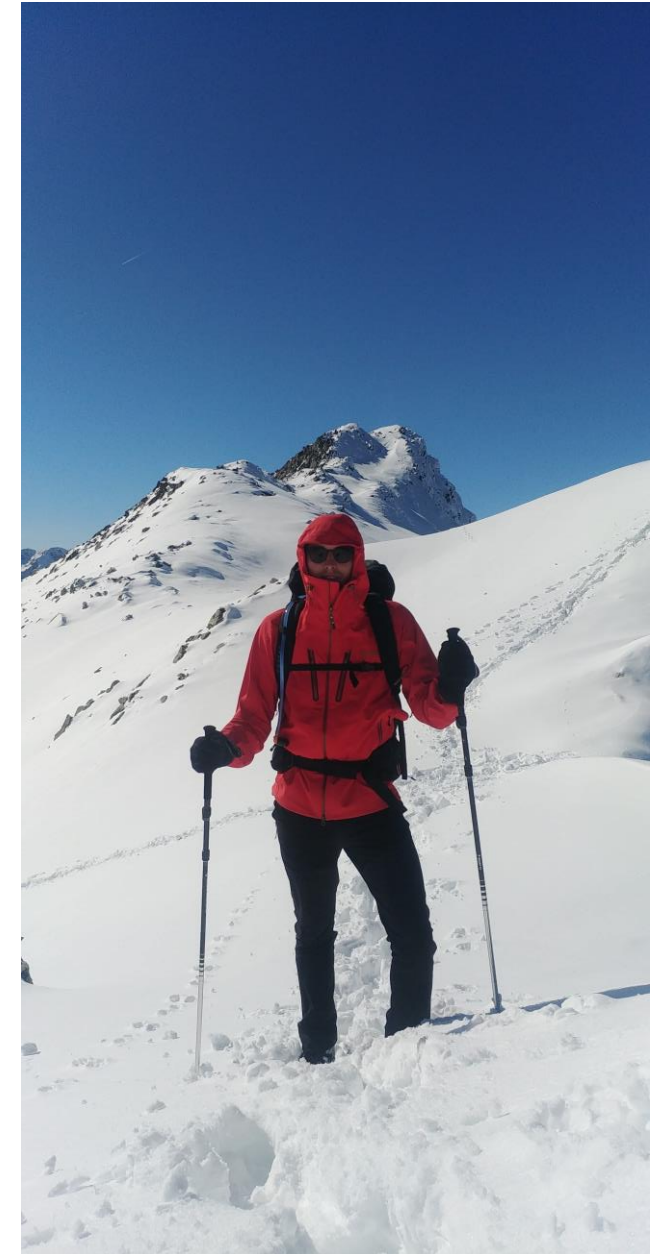




# Bilder und Eindrücke



# Bilder und Eindrücke





# Bilder und Eindrücke



Fragen?

Schreibt mir einfach eine E-Mail!

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