EPFL

Lecture 0
Introduction
2024-2025

ME-426 – Micro/Nanomechanical Devices

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École
polytechnique
fédérale
de Lausanne

Welcome!!!

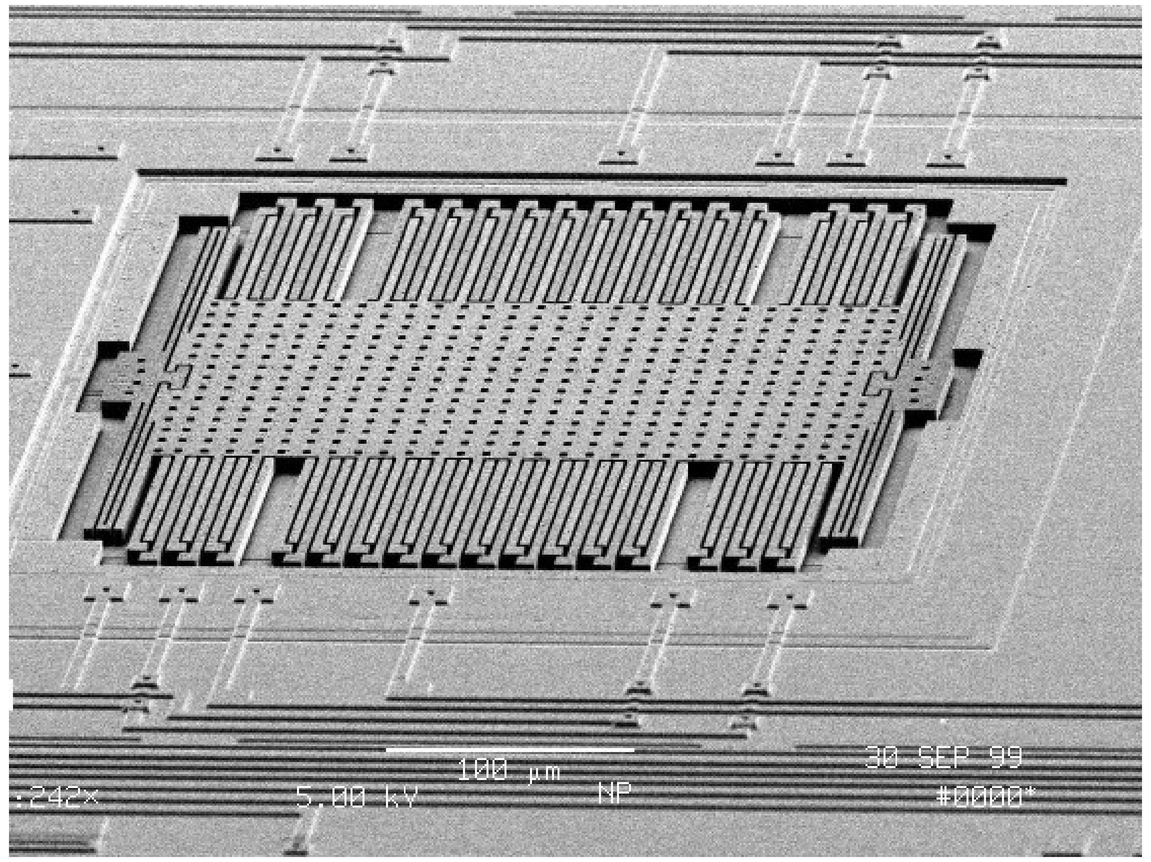
- Overall objectives of the course
- Organizational/Pragmatic matters
- “Schedule” for the semester

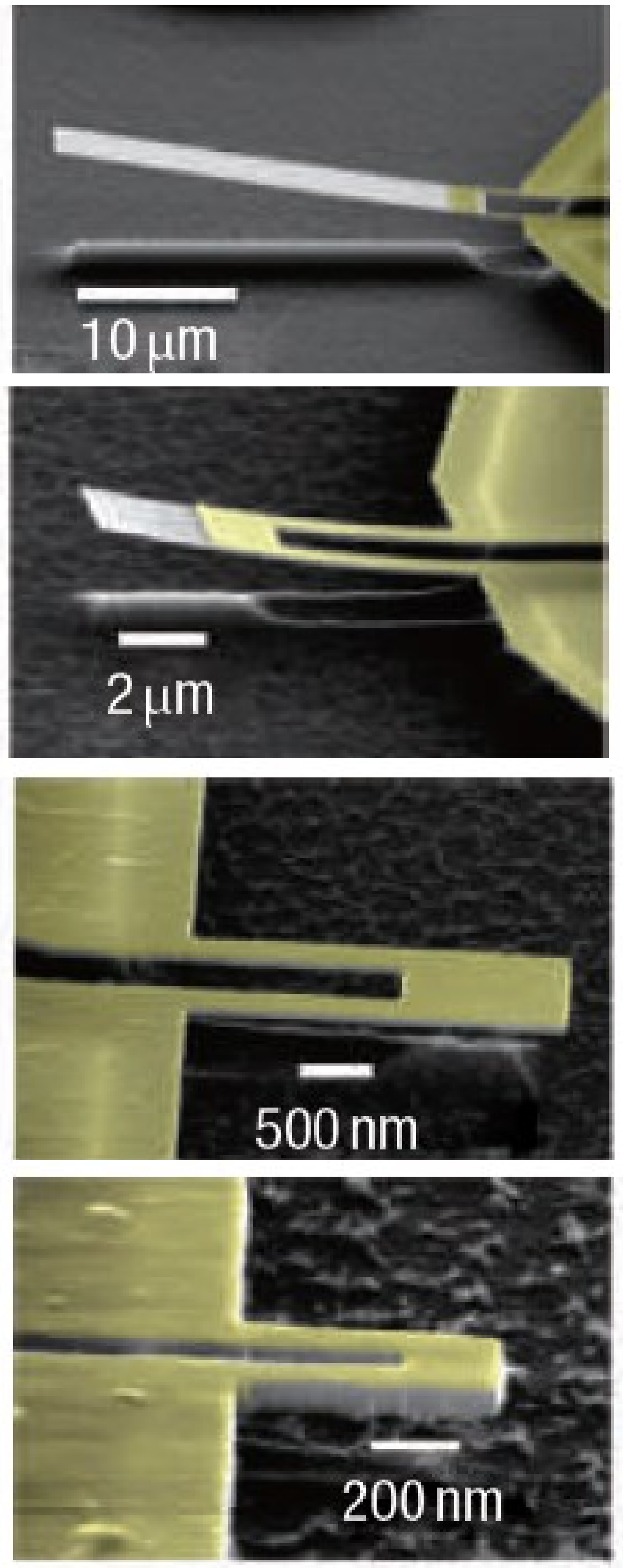
Who am I?

- 2002-2006 – PhD in CNM (Barcelona, Spain)
  - Static NEMS cantilevers for biomolecular detection
- 2007-2009 – PostDoc @ EPFL (LMIS1)
  - Novel Nanofabrication tools for NEMS
- 2009-2012 – Marie Curie PostDoc @ Caltech – Pasadena, California
  - Resonant NEMS – Nonlinear and coupled dynamics
- 2012-2013 – Marie Curie PostDoc @ DTU – Copenhagen, Denmark
  - Resonant M/NEMS – Dissipation and back-action mechanisms
- 2013-2022 - Assistant Professor @ EPFL – IMT-IGM
- 2022-... - Associate Professor @ EPFL – IGM
  - Advanced NEMS
    - Novel sensing schemes
    - Novel communication devices
- Check out our student projects!!!

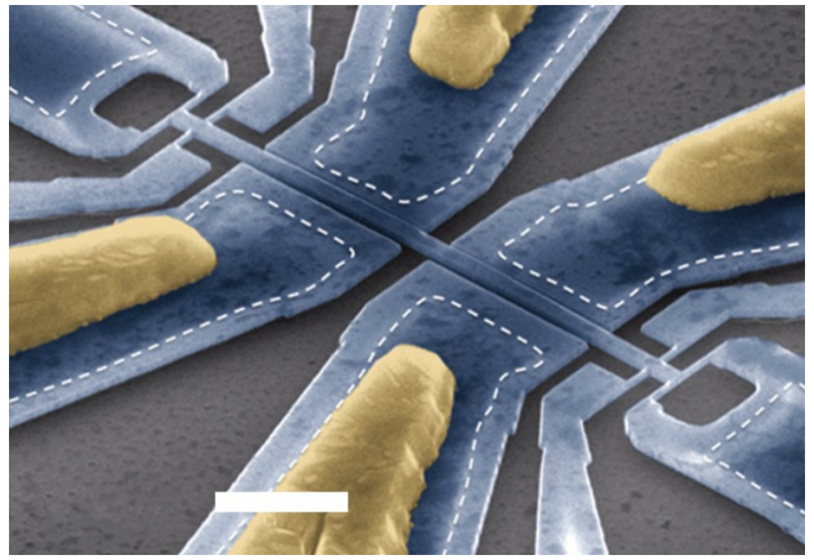
What's this course about?

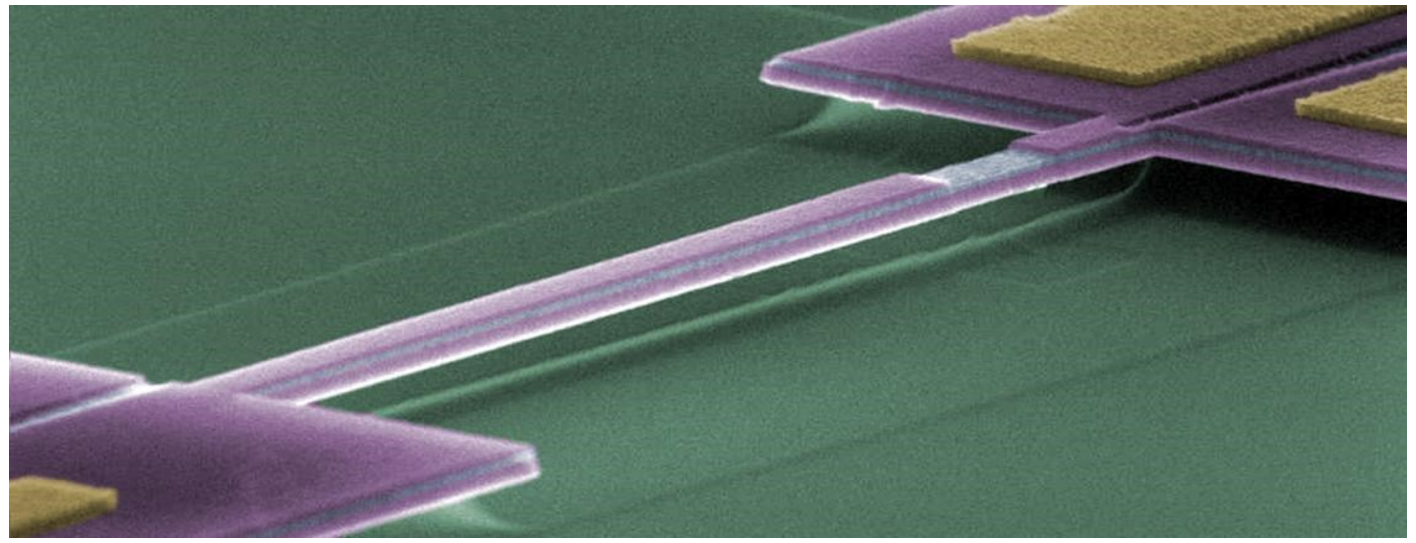
- Why reducing size???





MICRO/NANO





Overall objectives of the course

- Understand what is different in mechanical devices when you reduce dimensions down to the micro/nano-scale
- Introduce how these devices are designed and fabricated
- Understand the principle of transduction of the motion and introduce several techniques to perform it

- Introduce concepts like
  - Energy loss mechanisms
  - Nonlinear dynamic behavior
  - Thermomechanical noise

- Soft skills:
  - Reading papers and analyzing them
  - Discussing in group the contents of the papers

Key concepts

- Benefits of reducing size
- How to analyze composite structures
- Onset of nonlinearity (static, dynamic)
- Intrinsic stress
- Quality factor
- Thermomechanical noise
- Responsivity and Resolution

What this course is about

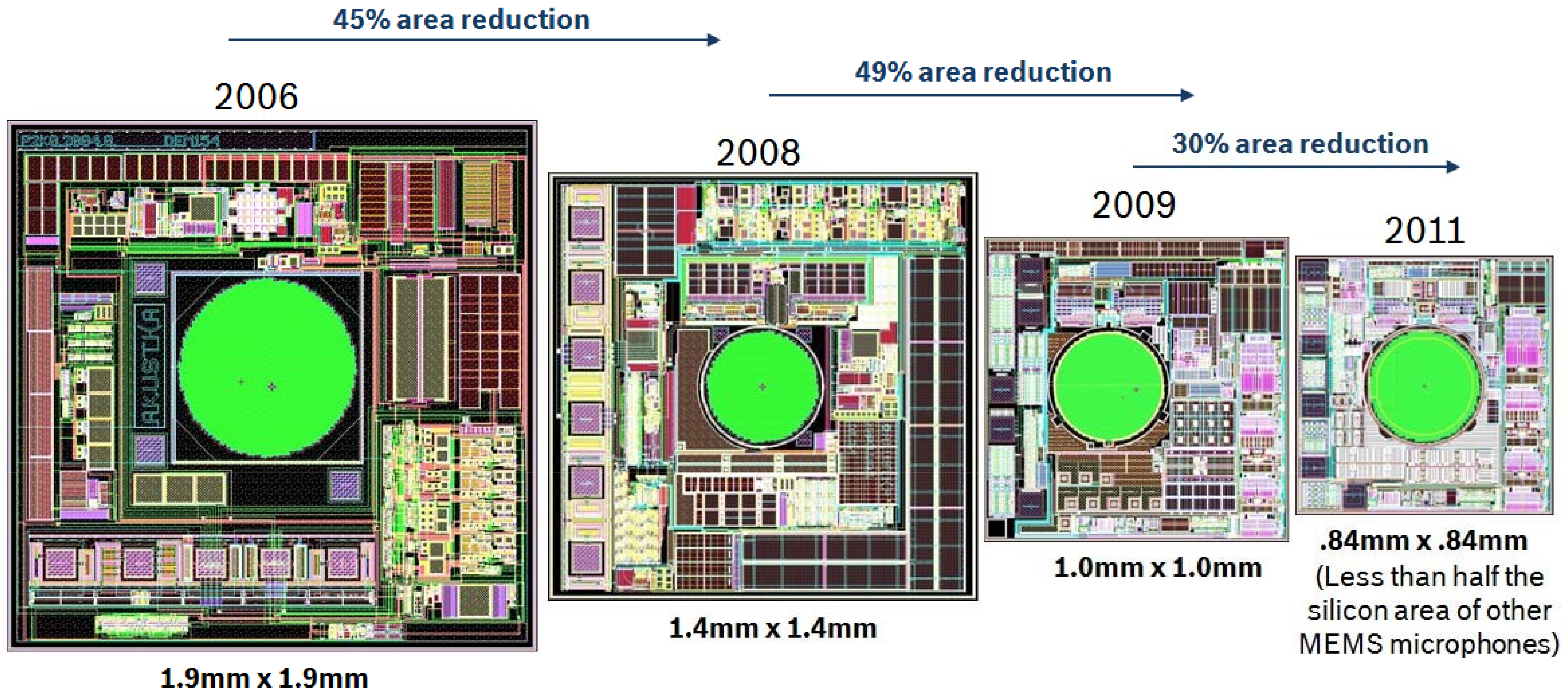
- Course for both SGM (most of you) and SMT

- At first it will be tougher for SGM students
  - Many concepts that SMT students have already seen

- Then it will get easier for SGM students

What this course is NOT about

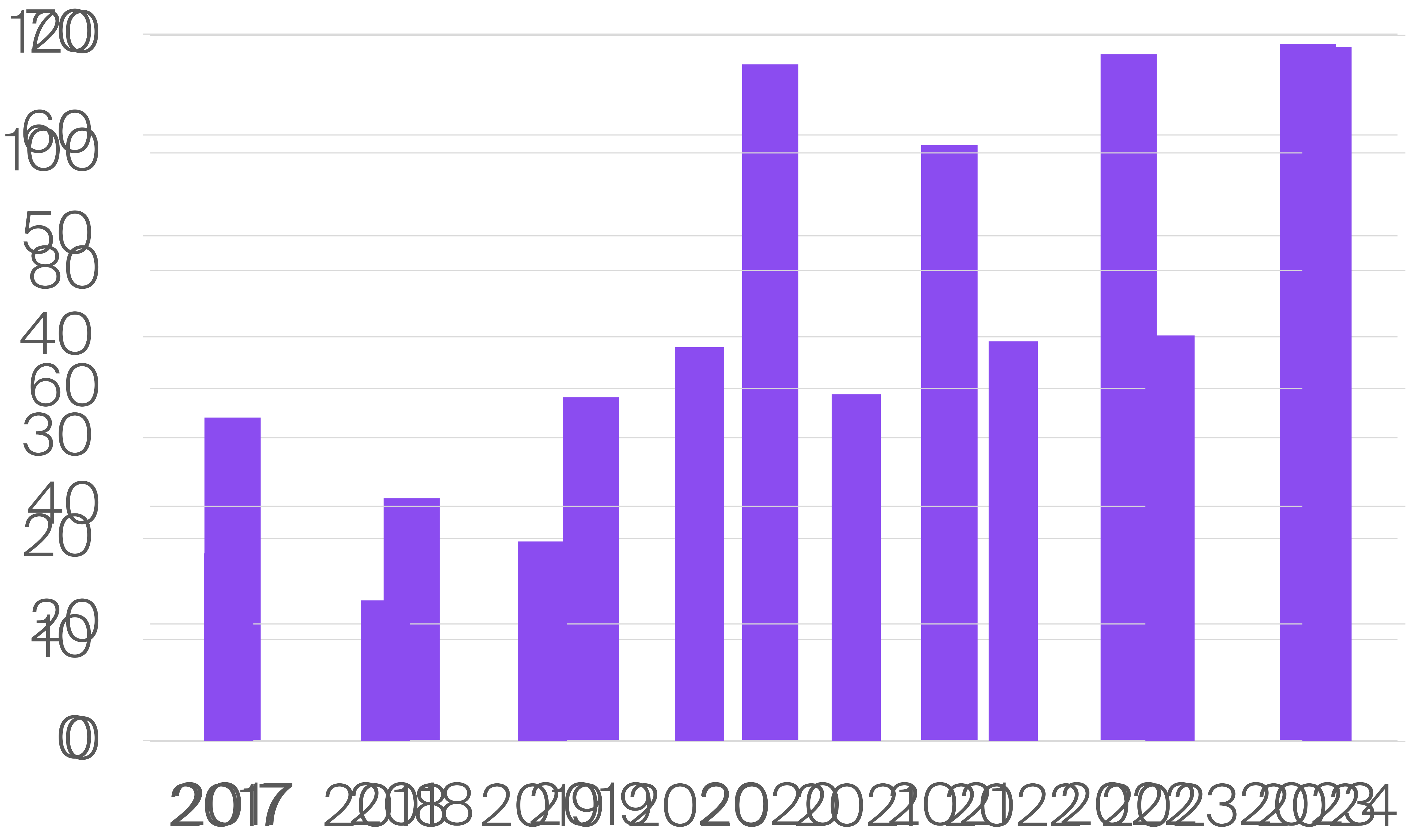
- We will remain at the "device" level
- In reality, commercial MEMS and NEMS are part of much more complex systems
  - E.g. Microphones:



- If interested in systems, you should check out the course
  - MICRO534 – Advanced MEMS (3 credits, Spring semester)

Practical matters

- Disclaimer:
  - We are not sure what will happen during the semester, so let's try to have fun and learn!
  - You are **118**, so I will have to adapt



Practical matters

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- Classes:
  - Splitting: 10h15-11h45 – 45 mins break – 12h30-14h00 (approx)
  - Lecture videos from last year already in MediaSpace
  - For paper discussions, I will record and upload the videos for this year
  - Exercises are these "paper discussions" and not every week – Better to be there

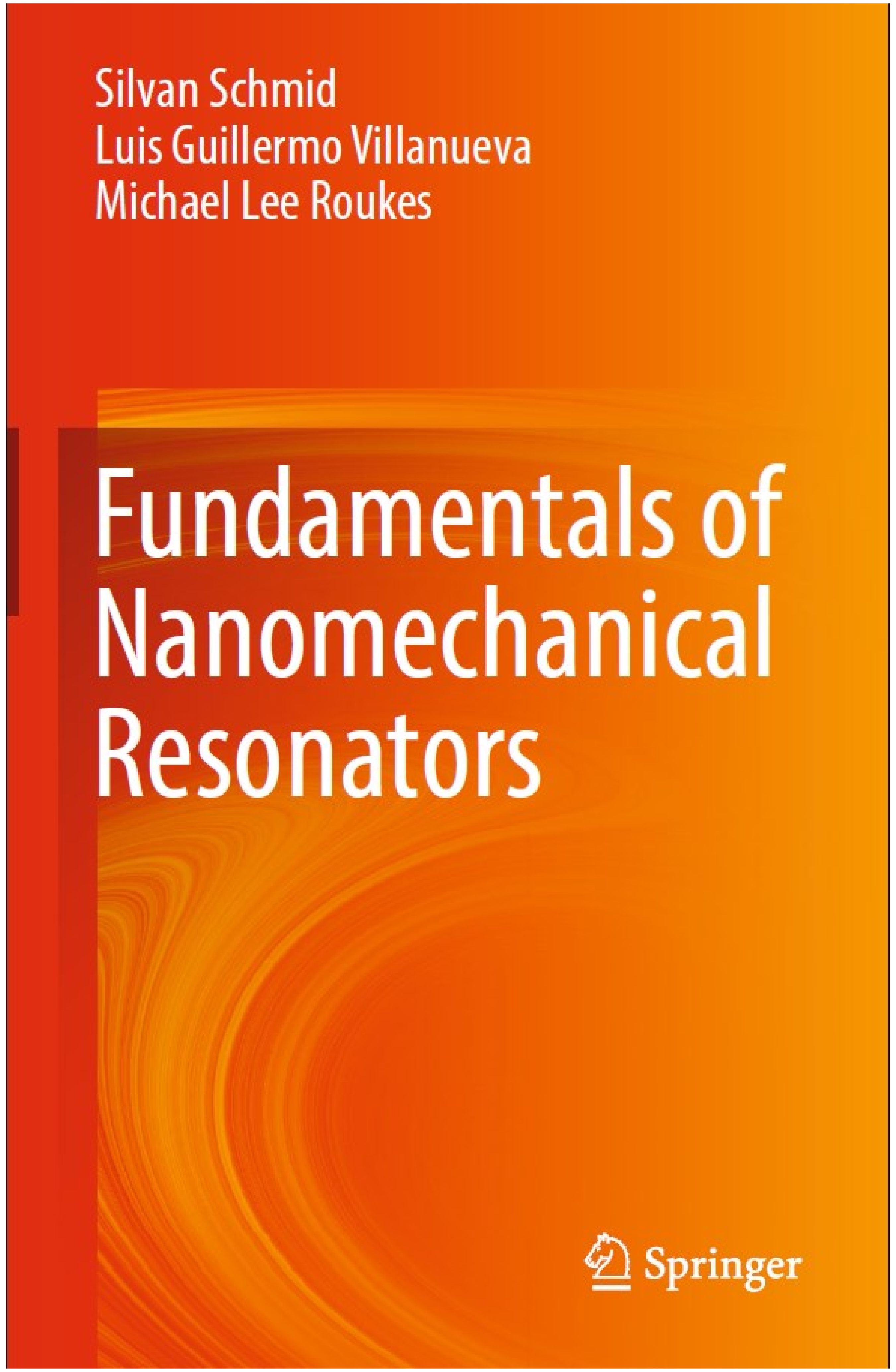
- Evaluation:
  - Discussions in class (10 interventions) – 20%
  - Exam (see later "Take home messages") – 80%

Practical matters – Course materials

- Lecture Videos:
  - [ME-426 Micro/Nanomechanical devices]
- Moodle:
  - https://moodle.epfl.ch/course/view.php?id=15503
  - Lecture slides WITH annotations
  - Papers to read
  - Paper discussions WITH annotations
  - Book as support material

Book

- Fundamentals of Nanomechanical Resonators
- Do NOT buy it, just get it online – it's for free from EPFL
- I already put it in moodle



Practical matters – Workload for you

- Come to class // Watch the lectures videos
  - Read parts of the book when needed

- Read EVERY PAPER (9 papers)

- Actively participate in the discussions around each paper (so better if you come)
  - You need 10 interventions during the discussions to get 20% of the grade
  - You can have 10 interventions on 1 paper, or around 1 per paper

- Exam – Please see Take Home messages

Practical matters – Schedule (will be updated)

Week	Day	Theory		
1	10.09	Introduction; Scaling laws, Fabrication*		
2	17.09	Transduction of the motion – Techniques		
3	24.09	Transduction of the motion – Techniques		Paper (1)
4	01.10			Paper (1)
5	08.10	Static deflection – Force, Linear behavior, Intro noise		
6	15.10			Paper (2)
7	29.10	Station deflection – Stress		Paper (3)
8	05.11	Dynamic behavior – Linear Analysis Dynamic behavior – Stress influence on frequency		
9	12.11	Dynamic behavior – Mode coupling Dynamic behavior – Nonlinearities, Parametric drive		
10	19.11			Paper (4)
11	26.11	Material properties – Size effects		Paper (5)
12	03.12	Quality factor – Energy losses		Paper (6)
13	10.12	Thermomechanical noise, Detection schemes		Paper (7)
14	17.12			Paper (8, 9)

Papers

- Paper 1 – Downmixing – Transduction
- Paper 2 – Cellular Force – Force sensing
- Paper 3 – Biomolecular recognition – Surface stress sensing
- Paper 4 – Absorption of light – Stress dependence of frequency
- Paper 5 – Mode Coupling
- Paper 6 – Nonlinearities in cantilevers
- Paper 7 – Stress dilution – Q in SiN
- Paper 8 – Hollow resonators
- Paper 9 – Single protein detection

For questions...

- Class time
  - Tuesdays 10h15-14h

- By email:
  - Guillermo.Villanueva@epfl.ch

Questions for the Exam

Exam (January)

- 5 questions, graded 0 – 0.5 – 1
- Random choice for everyone within the pool of questions (1 question per slide)
- Answers should be well known
  - Short time to answer (30 mins if written, 10 mins if oral)
- We can do it in English ou bien en Français o en Español o en Català (as you wish)

Take home messages

- Scaling laws
  - How does the mass, stiffness, frequency scale in the microscale?
  - Is gravity important in the microscale? How are reaction times in the microscale?
  - Can you give 3 examples for applications where MEMS/NEMS are useful?

- Fabrication (also from papers)
  - What is the major challenge when fabricating a mechanical device? What are the 2 main points to pay attention to solve this challenge? How can you solve them?
  - Do we need several materials for our devices? What can this cause in the structure?
  - What is an SOI wafer? What advantages does it provide for MEMS/NEMS?
  - What are the pros/cons of using polymers to make your MEMS/NEMS?
  - Choose one paper (1-9) and succintly describe the fabrication process

Take home messages

- Transduction of the motion
  - What are the two most used actuation (of the motion) principles for NEMS/MEMS? Explain how one of them works
  - What are the two most used detection (of the motion) principles for NEMS/MEMS? Explain how one of them works
  - What is background? What is signal to background ratio? How can we improve this SBR?
  - What is the difference between noise and background?
  - What different types of nonlinearity can we have in the transduction of the motion?
  - What does it mean to perform a "balanced measurement" and why is it important/useful to do so? (give also an example)
  - What is down-mixing? What advantages does it provide? (write formulas)
  - What is measurement bandwidth? Why is this an issue for smaller devices?

Take home messages

- Force/Stress
  - What do we want in a structure to have a great force responsivity? Discuss dimensions, material properties, etc.
  - What is dynamic range of a sensor? What limits our dynamic range in static?
  - What do we want in a structure to make a great surface stress sensor? Discuss dimensions, material properties, etc.
  - What can we use a surface stress sensor for? (2 examples)
  - How important is it to have a reference device for sensing? How would you design it? Illustrate with an example.
  - In paper 2
    - Which forces are going to be detected?
    - How important is the geometry of the metallic line?
    - Why in polymer?
  - In paper 3
    - Why in Silicon?
    - Why the metal on top? And on the bottom?

Take home messages

- Dynamical behavior (single)
  - What are eigenmodes and eigenvalues of a structure? Are they orthogonal? What do they depend on?
  - What happens to the eigenmodes and eigenvalues with stress?
  - What changes when we change the normalization constant of the modes?
  - What are the effective mass and effective stiffness (write formulas)? What do they depend on?
  - What is dynamic nonlinearity? Different possible origins?
  - For which magnitudes can we use the frequency as a sensing parameter?
  - How does Temperature affect a resonator and its resonance frequency? (different effects depending on the type of resonator)
  - When a single (punctual) mass lands on a resonator - What changes? Does it depend on the landing position? Can we detect the mass?
  - When mass arrives to a resonator distributed over its surface - What changes? How is it different than single (punctual) mass landing?
  - When a mass flows through a hollow resonator - What changes? How is it different than single (punctual) mass landing?

Take home messages

- Dynamical behavior (coupled)
  - What happens when we connect two resonators via a mechanical clamp? How does the effect depend on the resonators and clamp properties?
  - Why can we have coupling within a single beam? What is the origin of that coupling? What does it imply for the modes?
- Size effects
  - What happens to the Young's modulus when thickness reduces?
- Quality factor
  - What is the quality factor?
  - What are the typical energy loss mechanisms we should pay attention to?
  - What are the two regimes for viscous losses on resonators? How can we reduce this effect?
  - How does stress affect the quality factor?
- Noise
  - What types of noise are important for mechanical devices?
  - Where does thermomechanical noise come from?
  - What is the Allan Deviation? How can we reduce it?