Porous materials:

from acoustic absorption to strut elasticity

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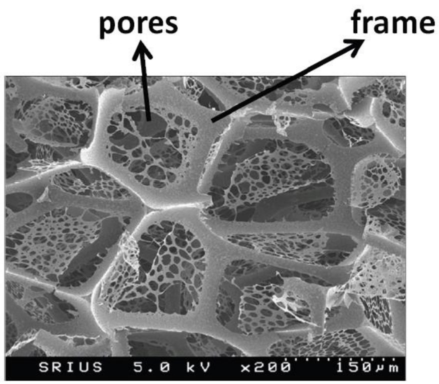
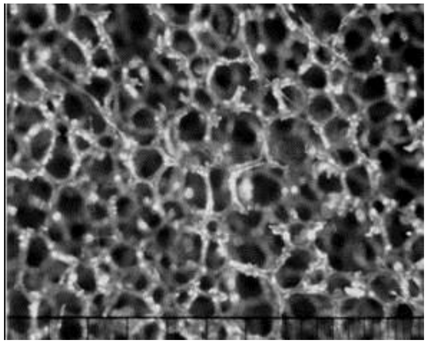
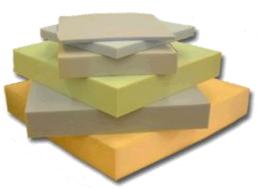


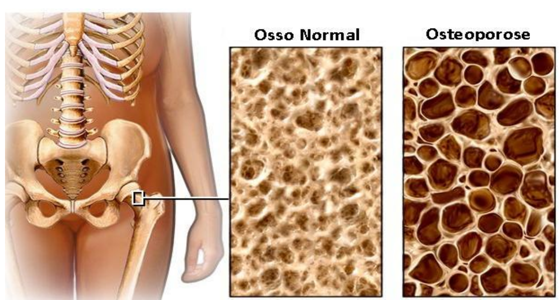
KU LEUVEN

Applications of porous materials
and
their importance
for
room and building acoustic quality

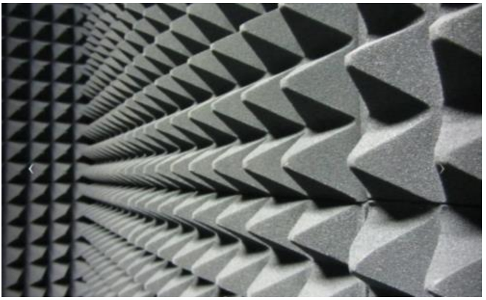
Porous materials: from acoustic absorption to strut elasticity



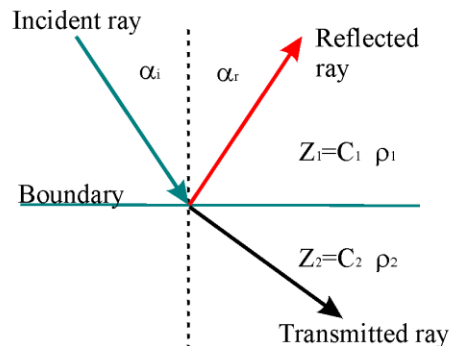




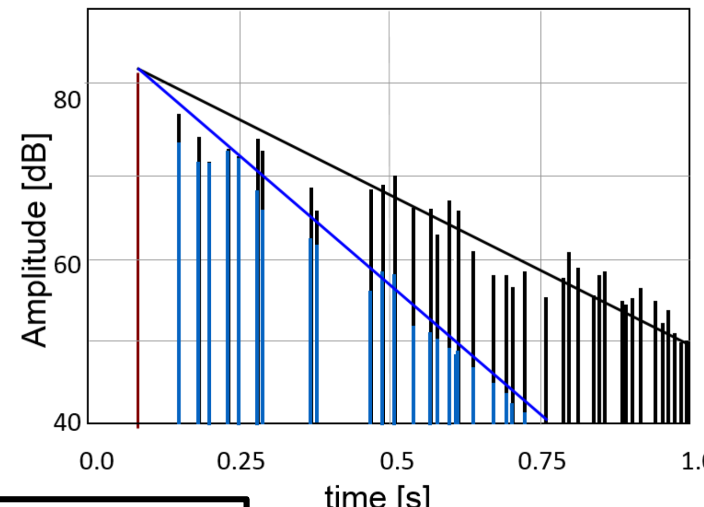
Porous materials : applications and effects in room acoustics



Reflection/transmission model

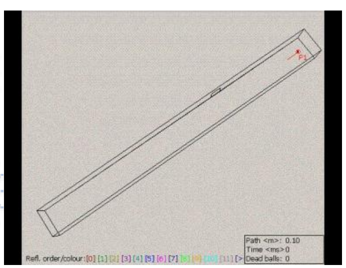


$$T_{60} = \frac{0.16V}{\bar{\alpha} S_{tot}}$$



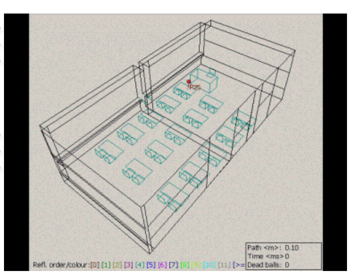
delta

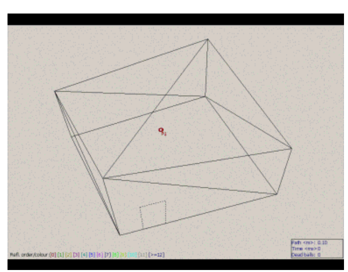
delta
reverb 5 s



music

music
reverb 5s





higher acoustic absorption
⇓
shorter reverberation time
⇓
better speech intelligibility

Acoustic parameters

- impedance Z~ρc
- reflection R_I ~ ΔZ
- absorption α=1-R_I
- scattering s

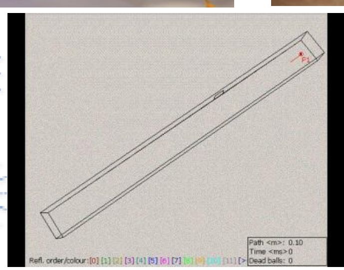
Porous materials : applications and effects in room acoustics

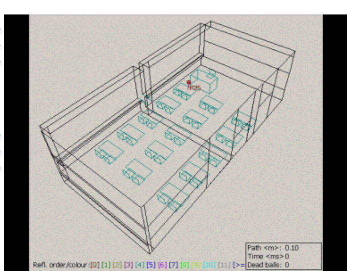
delta

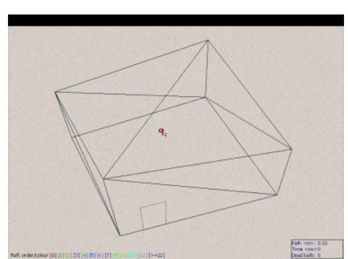
delta reverb 5 s

music

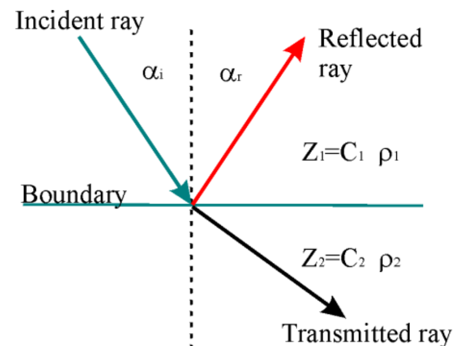
music reverb 5s



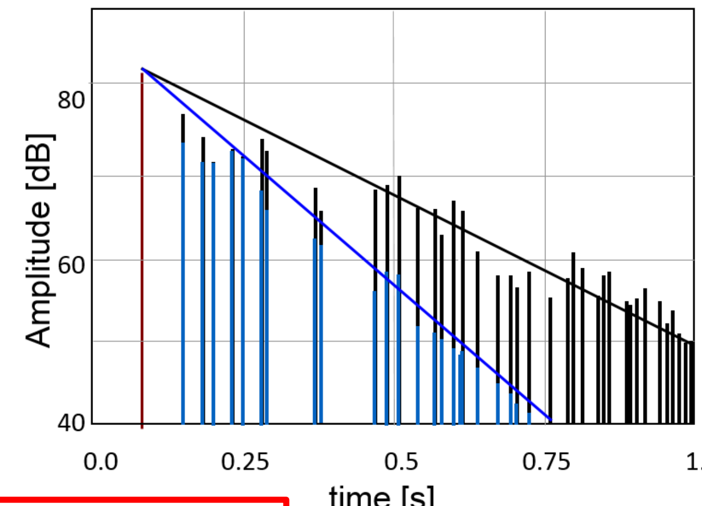




Reflection/transmission model



$$T_{60} = \frac{0.16V}{\bar{\alpha} S_{tot}}$$

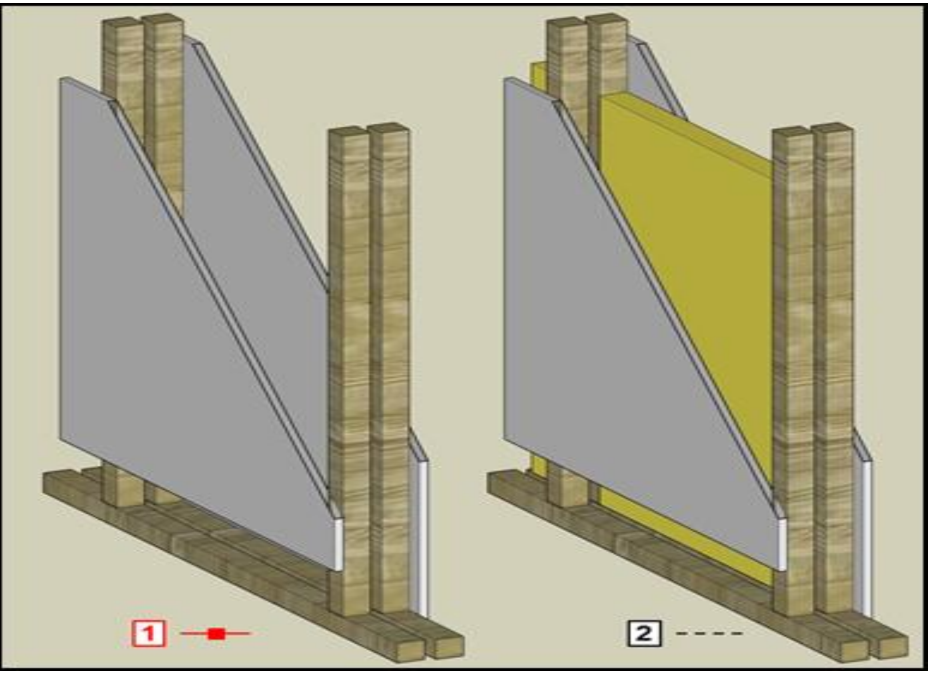


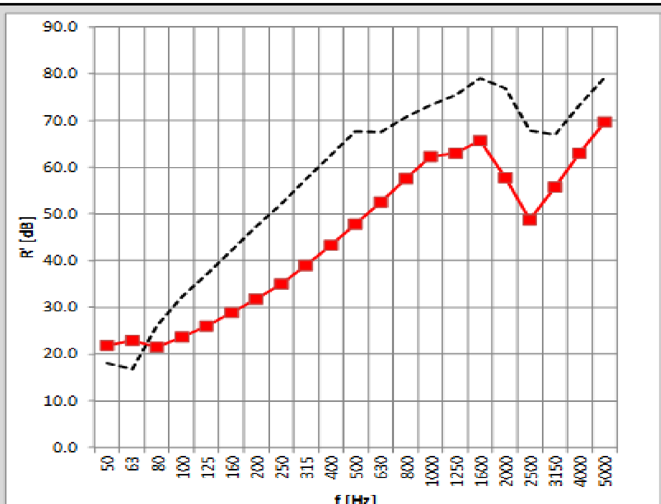
higher acoustic scattering
⇓
more uniform distribution of sound energy
⇓
better acoustic performance

Acoustic parameters

- impedance Z~ρc
- reflection R_I ~ ΔZ
- absorption α=1-R_I
- scattering s

Porous materials : applications and effects in building acoustics

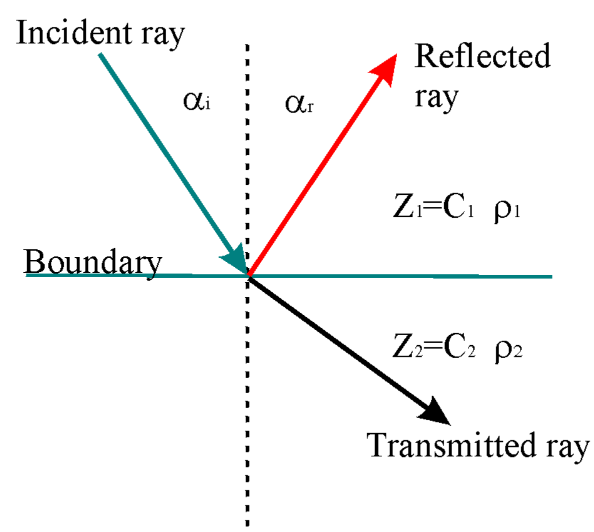




f [Hz]	1	2
50	21.9	18.0
63	23.0	16.7
80	21.5	25.9
100	23.7	32.3
125	26.0	37.0
160	28.8	42.3
200	31.7	47.2
250	35.1	52.2
315	38.9	57.4
400	43.4	62.7
500	47.8	67.7
630	52.5	67.5
800	57.5	70.7
1000	62.3	73.3
1250	63.0	75.4
1600	65.7	79.1
2000	57.8	76.9
2500	48.8	67.9
3150	55.8	67.0
4000	63.0	73.3
5000	69.7	79.2

1	R'_{living}= 45 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R'_w = 46 dB
2	R'_{living}= 51 dB	$C_{50-5000}$= -10 dB	$C_{100-3150}$= -4 dB	R'_w = 61 dB

Reflection/transmission model



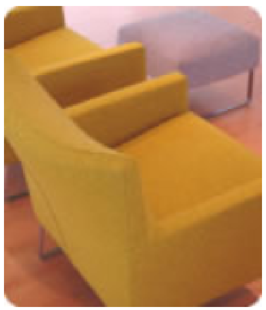
Acoustic parameter
- absorption α

Porous materials : applications and effects in vibration damping

VISCOELASTIC POLYURETHANE FOAM

Slow recovery after compression
- mattresses
- pillows,
- wheel chair pads
- furniture

HIGH RESILIENCE POLYURETHANE FOAM

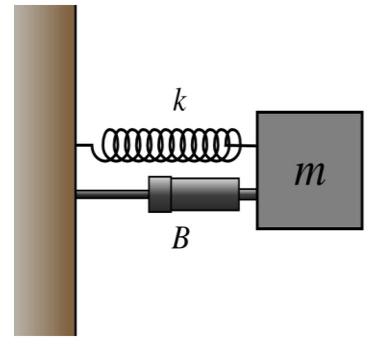


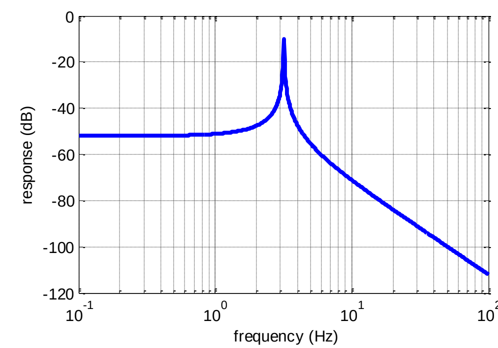
Non-uniform and open cell structure
- high resilience foam
- bedding
- furniture
- footwear

MICROCELLULAR POLYURETHANE FOAM

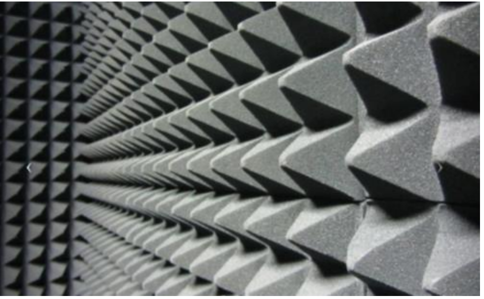
Very fine cells: light but strong
- Furniture arm rests
- Wheel chair wheels
- Replacement of plastic

Mass-spring model





Viscoelastic parameters:
- spring constant
- real and imaginary part of
  - longitudinal modulus
  - shear modulus

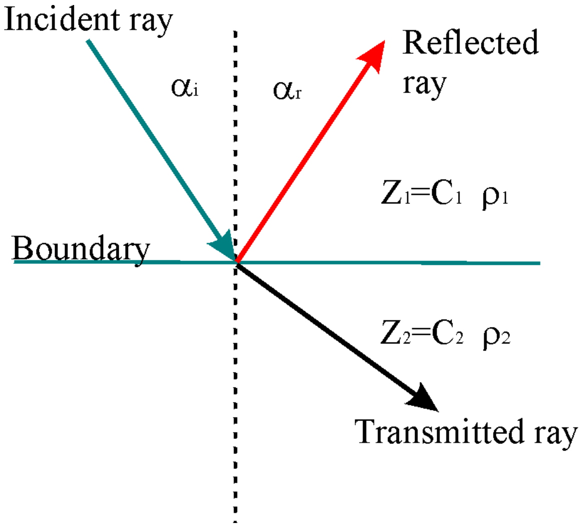


Measurement of
the acoustic performance
of
macroscopic porous surfaces

Porous materials for room acoustics : characterization methods

Determination of acoustic absorption

Geometry	Method
1. Random incidence	Reverberation
2. Perpendicular incidence	Kundt tube
3. Incidence under particular angle	a. Spark method
	b. Acoustic holography



$$I_{reflected}(f) = R_I(f) I_{incident}(f) = \left(1 - \alpha(f)\right) I_{incident}(f)$$

Porous materials for room acoustics : characterization

Determination of acoustic absorption

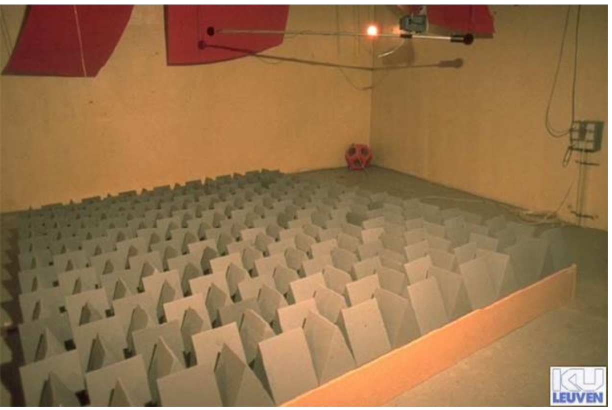
Geometry		Method
1. Random incidence	*ISO-354*	Reverberation

Without sample: $T_{60,without} = \frac{0.16V}{\alpha_{walls}S_{walls} + \alpha_{floor}S_{floor}}$

With sample: $T_{60,with} = \frac{0.16V}{\alpha_{walls}S_{walls} + \alpha_{sample}S_{floor}}$

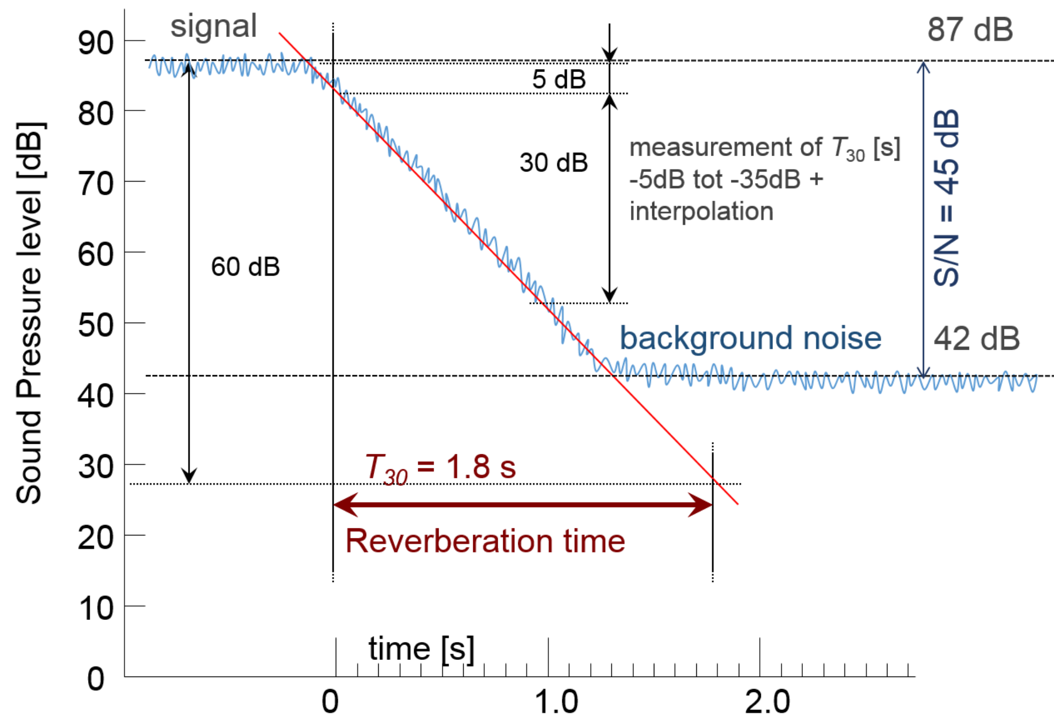
$$\alpha_{sample} = \frac{1}{S_{floor}}\left(\frac{0.16V}{T_{60,with}} - \alpha_{walls}S_{walls}\right) = \frac{1}{S_{floor}}\left(\frac{0.16V}{T_{60,with}} - \frac{0.16V}{T_{60,without}} + \alpha_{floor}S_{floor}\right)$$

Measurement of the reverberation time



with sample

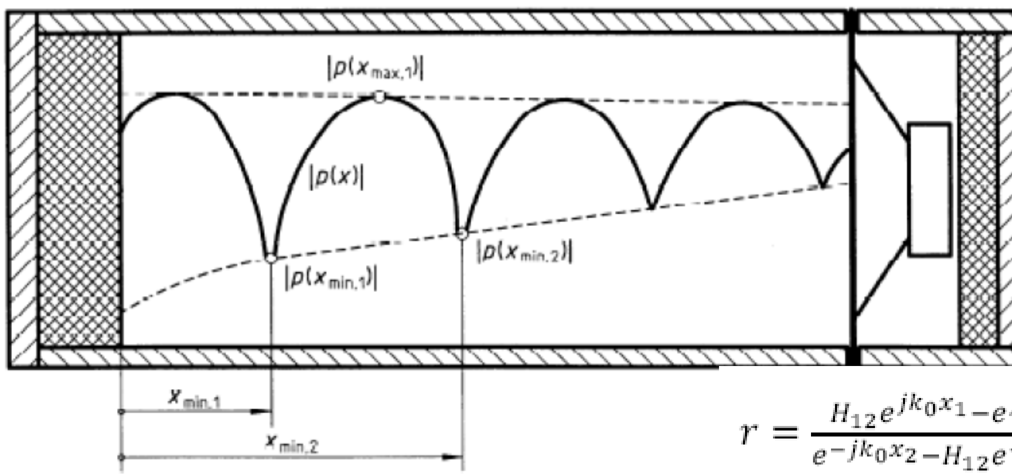
without sample



Porous materials for room acoustics : characterization

Determination of acoustic absorption

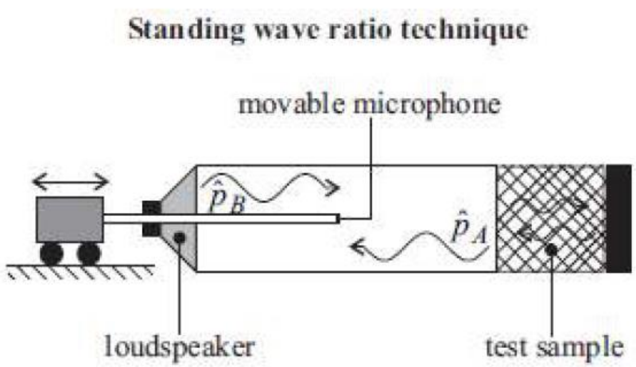
Geometry	Method
2. Perpendicular incidence *ISO-10534*	Kundt tube

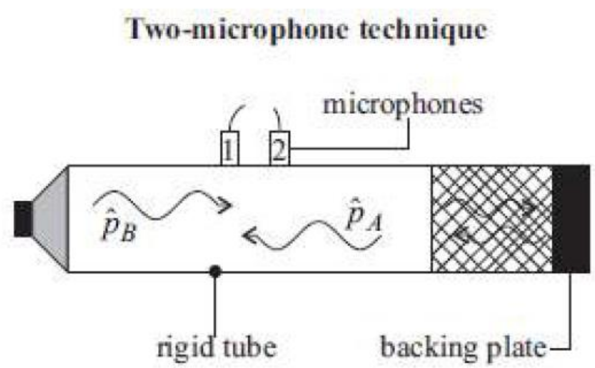


$$R_I = \frac{\frac{Z}{Z_0} - 1}{\frac{Z}{Z_0} + 1}$$

$$r = \frac{H_{12} e^{jk_0 x_1} - e^{jk_0 x_2}}{e^{-jk_0 x_2} - H_{12} e^{-jk_0 x_1}} = \frac{H_{12} - H_I}{H_R - H_{12}} e^{2jk_0 x_1}$$

Measurement of the reflection coefficient

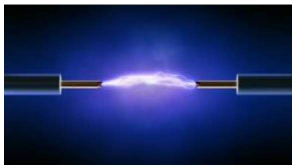


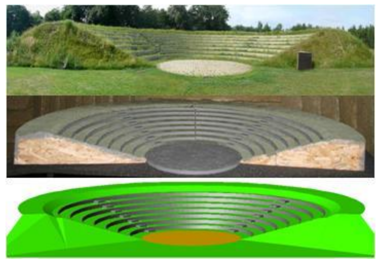


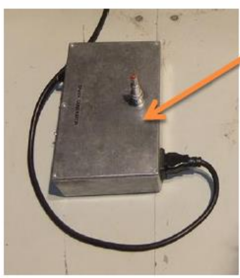
Porous materials for room acoustics : characterization

Determination of acoustic absorption

Geometry	Method
3. Incidence under particular angle	a. Spark method





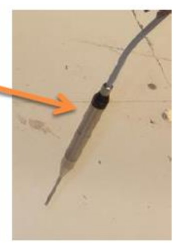


Spark source

The spark source provides an electrical pulse and produces electromagnetic waves.

Microphone

The microphone receives the acoustic signal and converts it into an electrical signal.



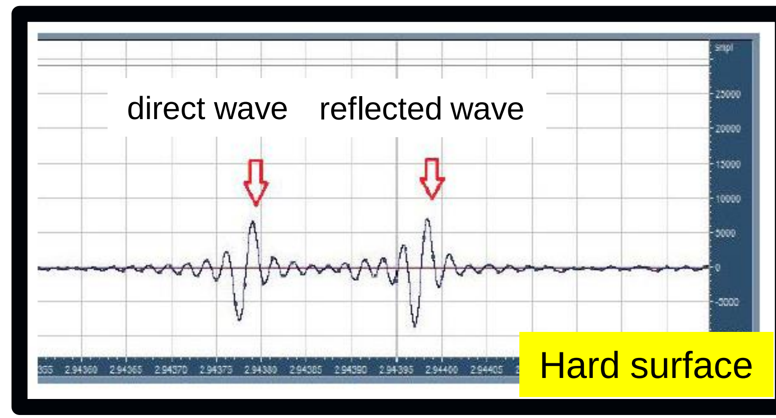
Pre-amplifier

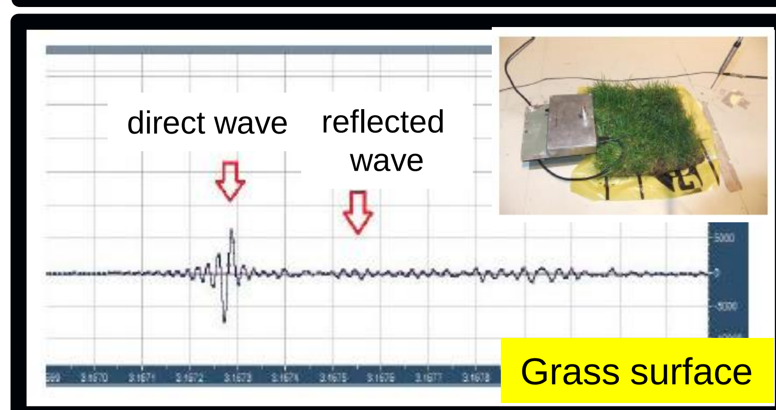
The pre-amplifier limits signal degradation caused by noise interference.

Sound Card

The sound card can manage all sounds received and send them to a computer.

Measurement of the reflection coefficient



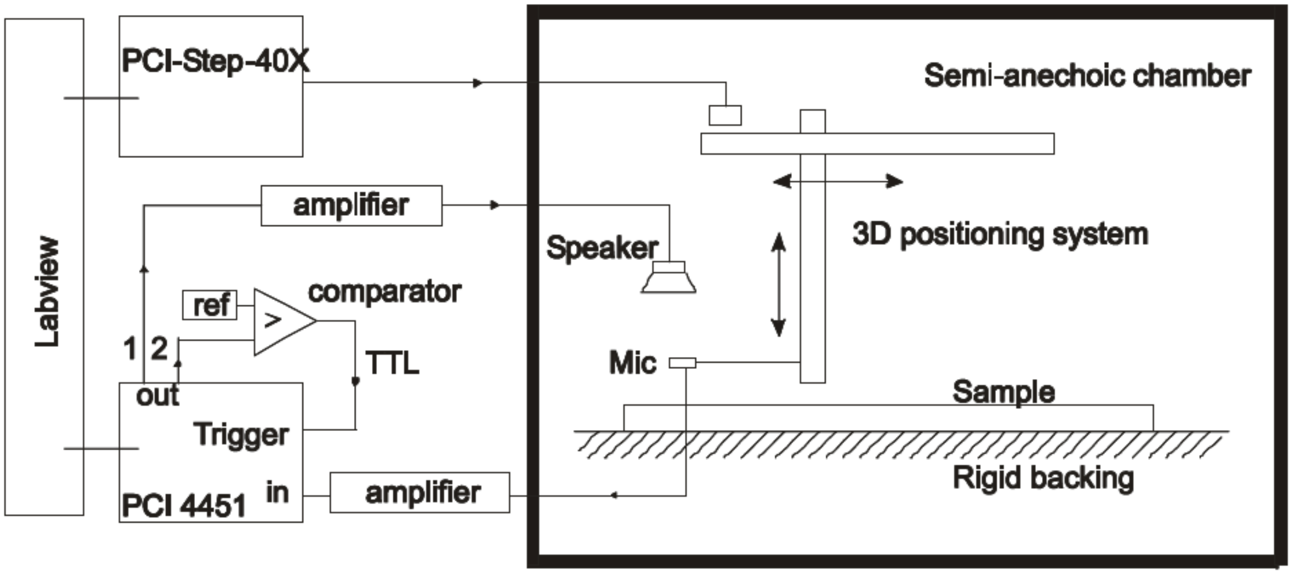


Porous materials for room acoustics : characterization

Determination of effective porous material parameters

Geometry	Method
3. Incidence under particular angle	b. Acoustic holography

Measurement of the reflection coefficient: Tamura method



$$R(k_x, k_y, k_z) = \frac{e^{-jk_z z_1} - e^{-jk_z z_2} \dfrac{P(k_x, k_y, z_1)}{P(k_x, k_y, z_2)}}{e^{jk_z z_2} \dfrac{P(k_x, k_y, z_1)}{P(k_x, k_y, z_2)} - e^{jk_z z_1}}$$

STUDY OF THE SOUND FIELD IN AND ABOVE POROUS MATERIALS-APPLICATION TO CHARACTERIZATION OF SOUND ABSORBING MATERIALS

PhD thesis Laurens Boeckx, KU Leuven, 2005

Measurement of the bulk properties of porous materials

Porous materials : characterization methods

Determination of structural parameters underlying the acoustic absorption

Geometry	Method
1. Compressive modulus of the frame	mass-spring/DMA
2. Shear modulus of the frame	mass-spring
3. Porosity	ultrasound reflection
4. Tortuosity	speed of sound
5. Thermal and viscous characteristic lengths	speed of sound
6. Flow resistivity	pressure-flow

Biot – Johnson – Allard - model

J. F. Allard and N. Atalla, *Propagation of Sound in Porous Media : Modelling Sound Absorbing Materials*, Elsevier (first edition 1993): Wiley and Sons. Ltd., New York, (second edition 2009)

Philippe Leclaire. Characterization of porous absorbent materials. Société Française d'Acoustique. Acoustics 2012, Apr 2012, Nantes, France. <hal-00810634>

Porous materials : characterization methods

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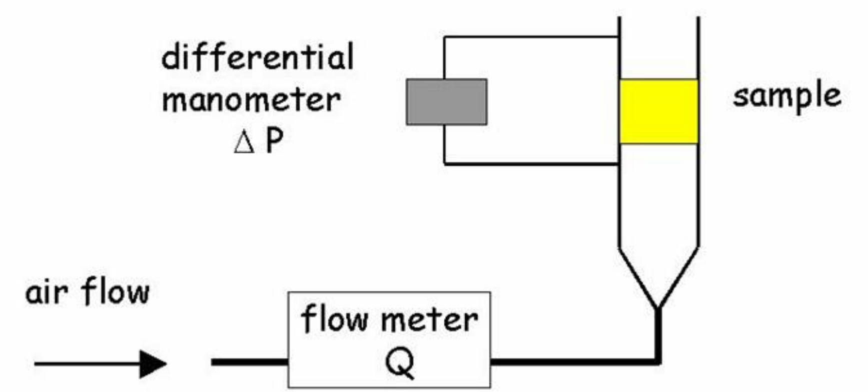
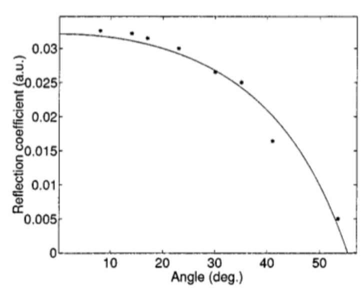
Flow resistivity R_{flow}

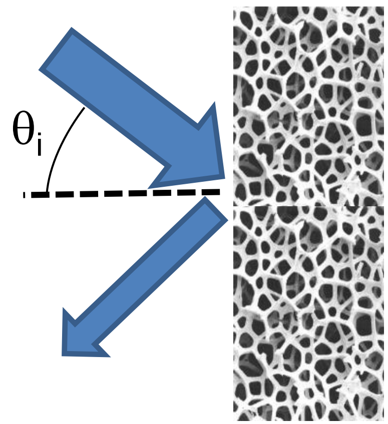


$$R_{flow} = \frac{pressure\ drop}{flow}$$

Porosity Φ

reflection coefficient $r_i(\theta,f)$





$$\phi = \frac{\alpha_\infty (1 - r_i)\cos\theta_i}{(1 + r_i)\sqrt{\alpha_\infty - \sin^2\theta_i}}$$

α_∞: tortuosity

Measuring the porosity and the tortuosity of porous materials via reflected waves at oblique incidence

Z. Fellah et al, J. Acoust. Soc. Am. **113**(5),2424(2003)

Porous materials : characterization methods

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Tortuosity α_∞, viscous (Λ) and thermal (Λ') characteristic length

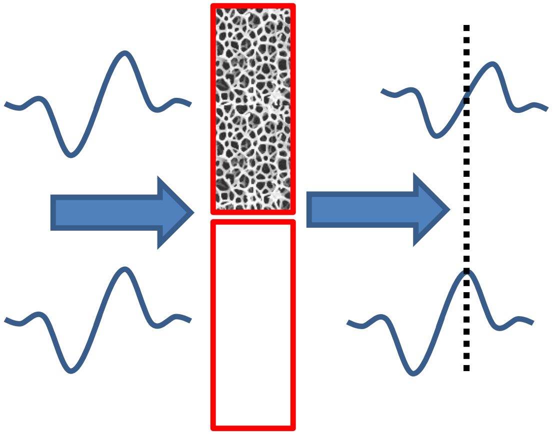
$$\alpha_\infty = \frac{1/V \int_V v^2 dV}{(1/V \int_V \vec{v}\, dV)^2}$$

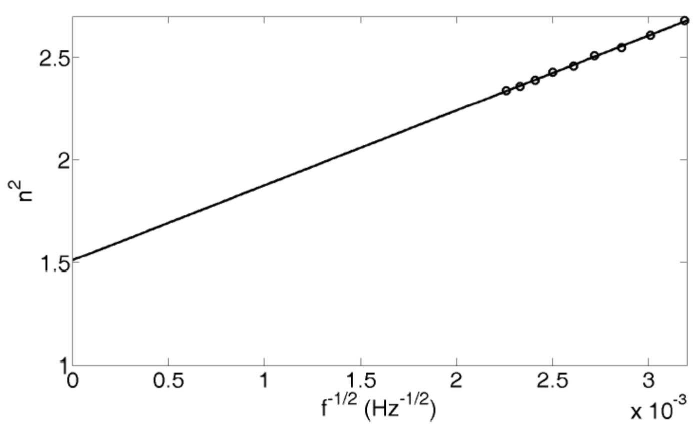
$$n^2 = \alpha_\infty [1 + \delta \cdot (\frac{1}{\Lambda} + \frac{\gamma - 1}{\Lambda' B})]$$

$n = \frac{c_{air}}{c_{sample}}$ refractive index

$\delta = \sqrt{\frac{2\eta}{\rho_f \omega}}$ viscous skin depth

B^2 Prandtl nr





Porous materials : characterization methods

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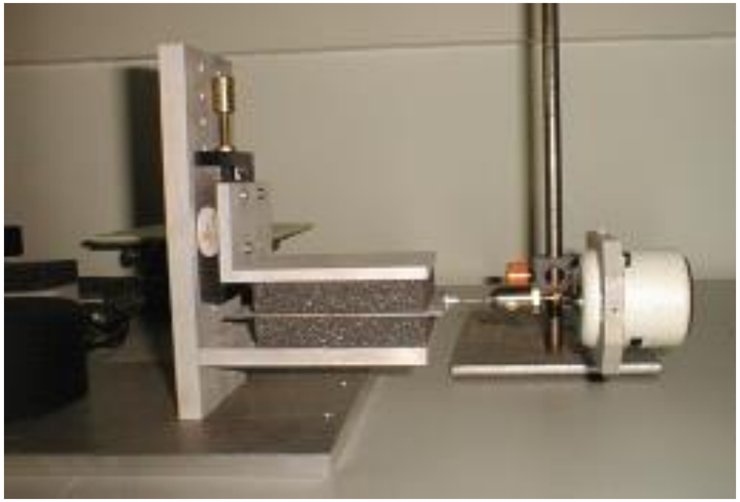
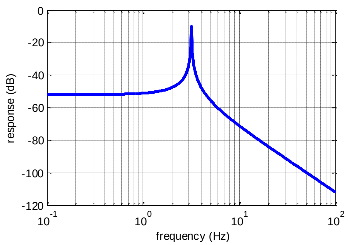
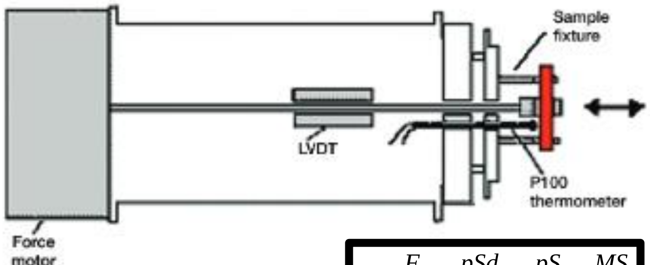
Mass-spring resonance experiment



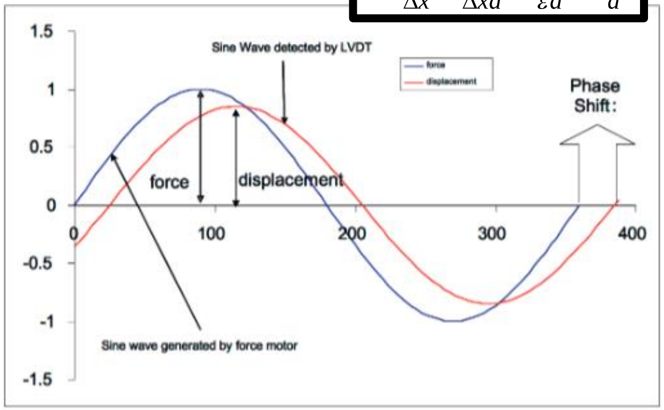


$$k = \omega_0^2 m = \frac{MS}{d}$$

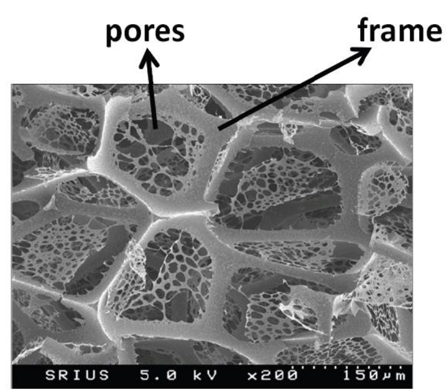
Dynamic mechanical analysis



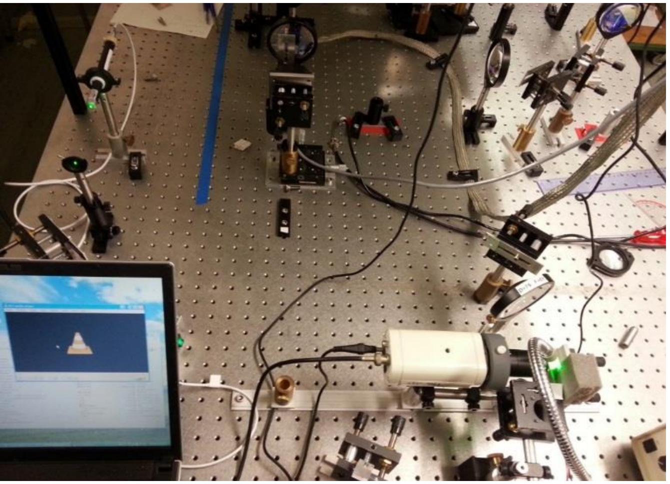
$$k = \frac{F}{\Delta x} = \frac{pSd}{\Delta x d} = \frac{pS}{\varepsilon d} = \frac{MS}{d}$$

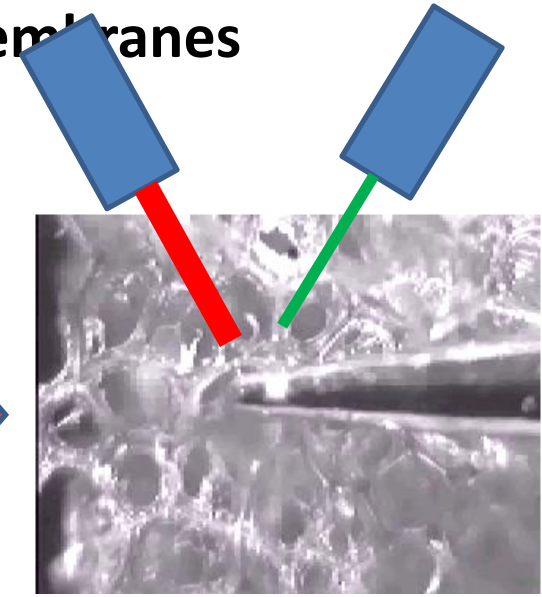


Measurement of
the microscopic properties
of
porous
struts and membranes



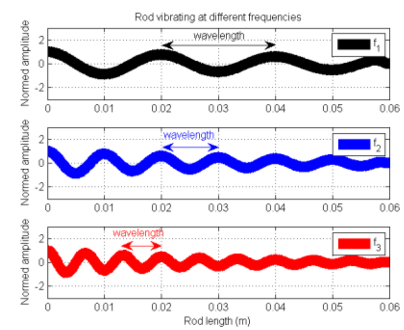
Characterization of porous struts and membranes





Approach:

- Local excitation: small source, short wavelength λ, high frequency f_{exc}
- Local detection:
  - CCD pixel size << λ, stroboscopic illumination frequency ~ f_{exc}
  - vibrometer probe spot size <<λ
- Local guided wave velocity and damping $\rightarrow$ local real and imaginary part of elastic modulus

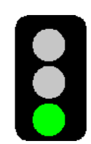


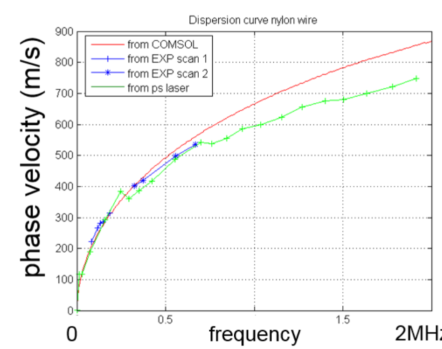
Challenge:

- Compromise between
  - Small wavelength λ: < microscopic entity of interest
  - Long wavelength λ: frequency $f=c/\lambda$ in the audio range

Strategy:

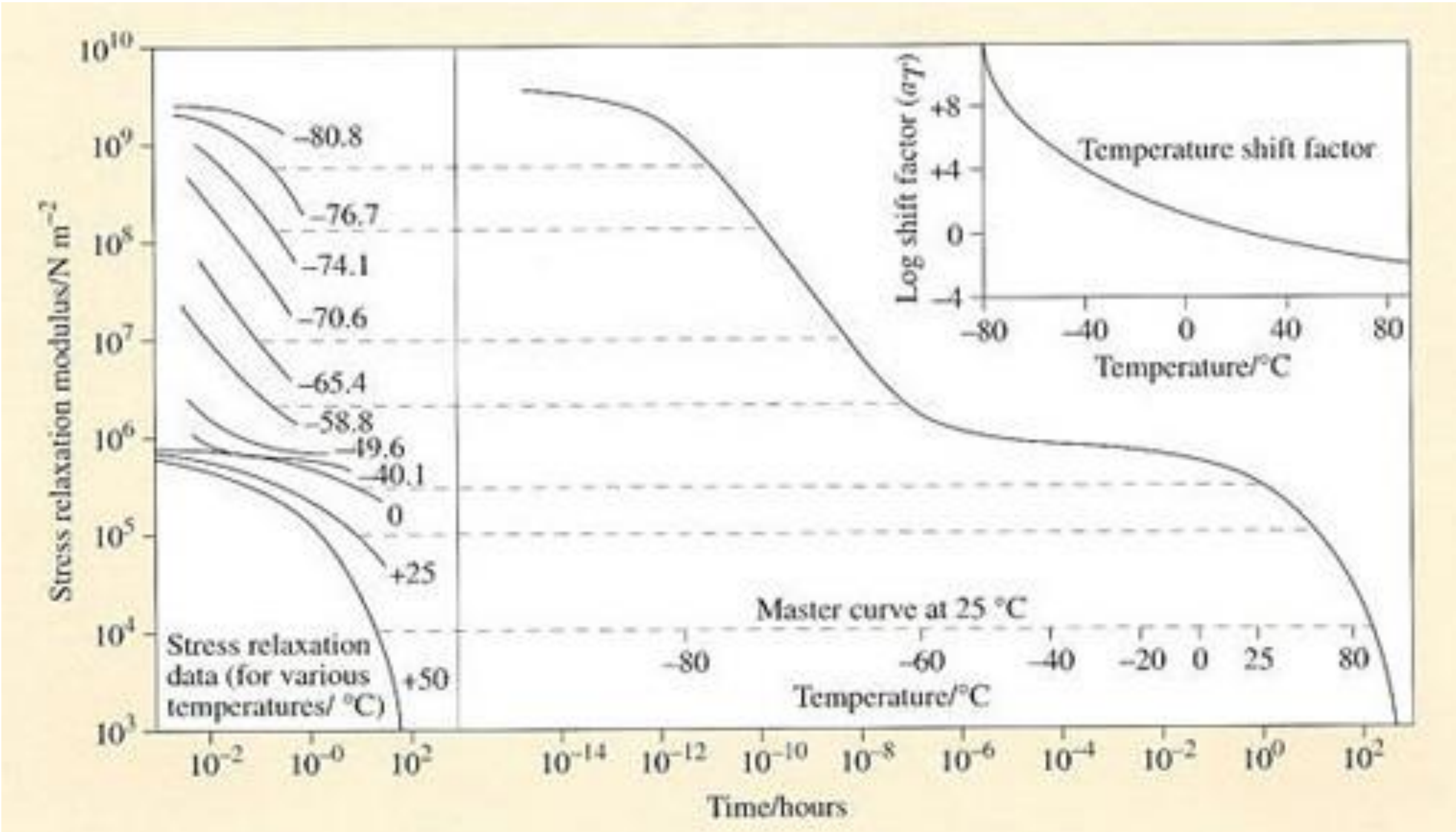
- Exploit time-temperature superposition principle





Porous materials: from acoustic absorption to strut elasticity

Time-temperature superposition principle



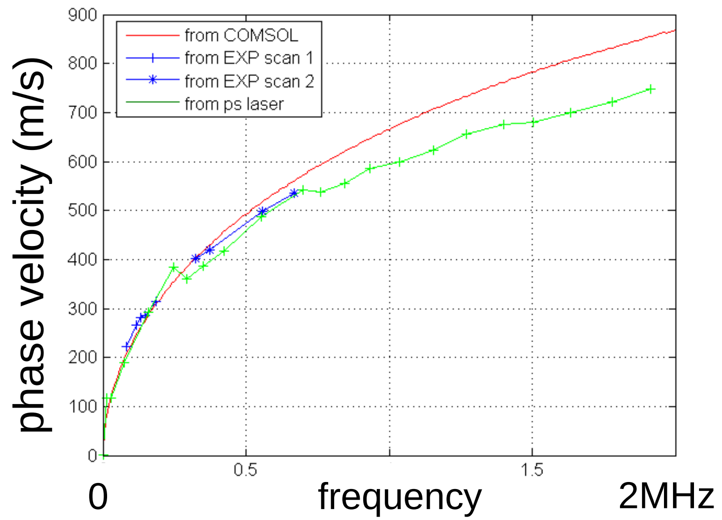
modulus $M(t,T_1)$
shift factor $\alpha_t(T_2/T_1)$
(e.g. Williams-Landel-FerryWilliams-Landel-Ferry (WLF) relation)

modulus $M(\alpha_t t,T_2)$

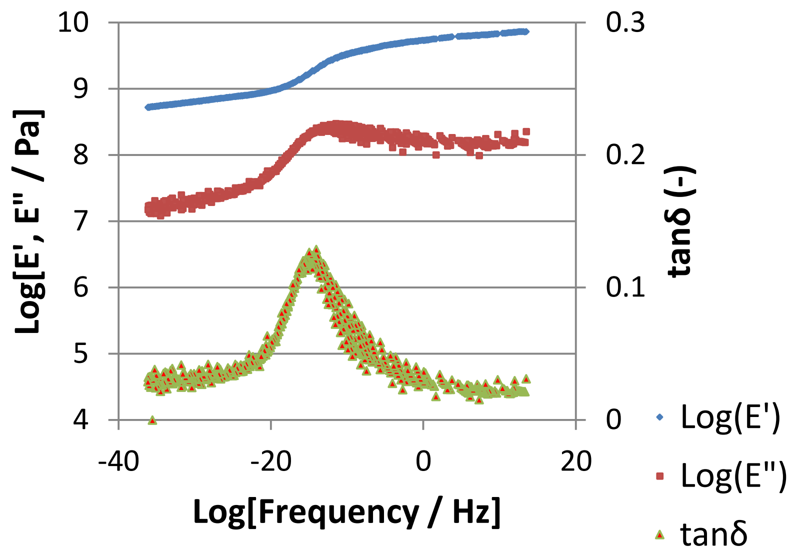
http://www.open.edu/openlearn/science-maths-technology/science/chemistry/introduction-polymers/content-section-5.3.1

Porous materials: from acoustic absorption to strut elasticity

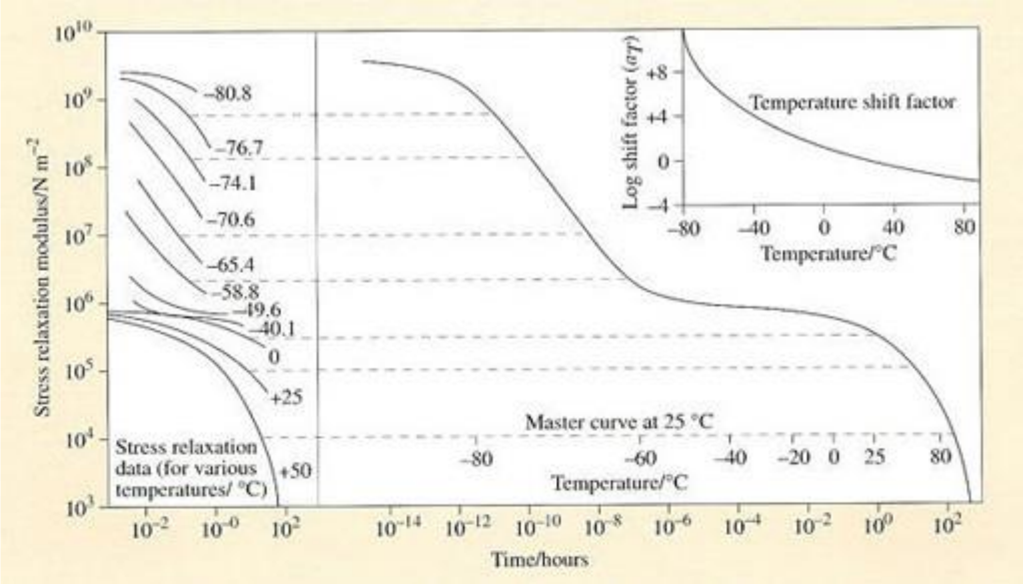
Vibrometry measurement on a nylon fiber



DMA measurement on a nylon fiber

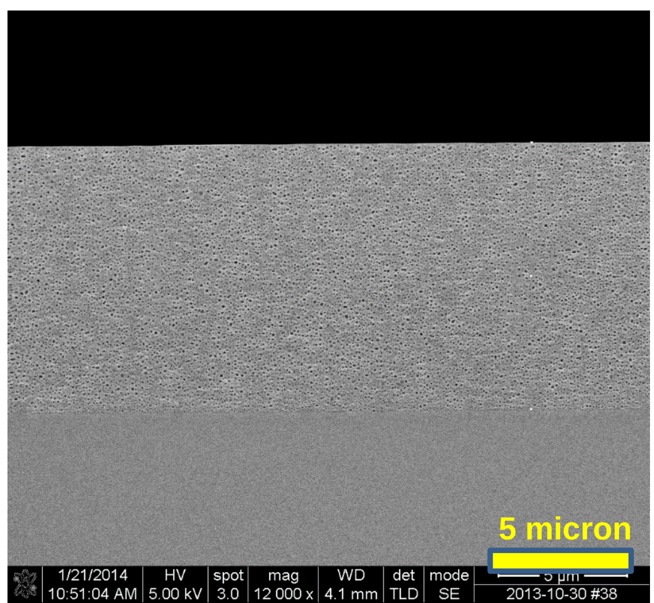


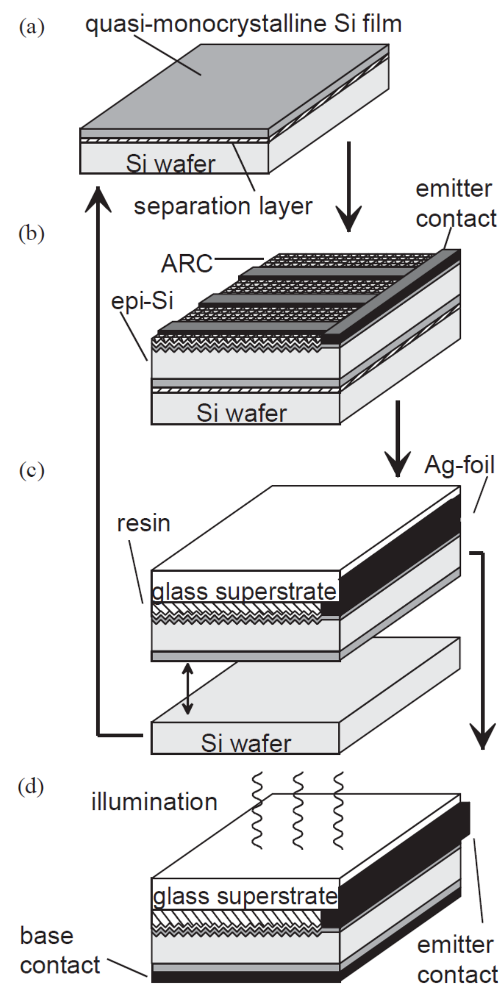
Time-temperature superposition principle



Porous silicon

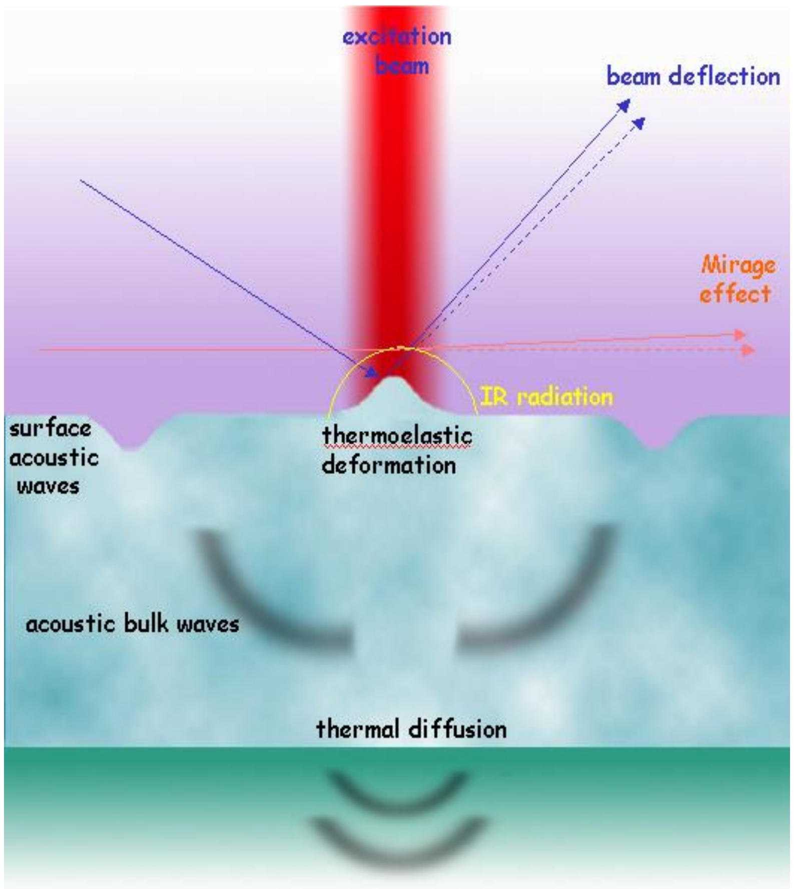
Porous silicon



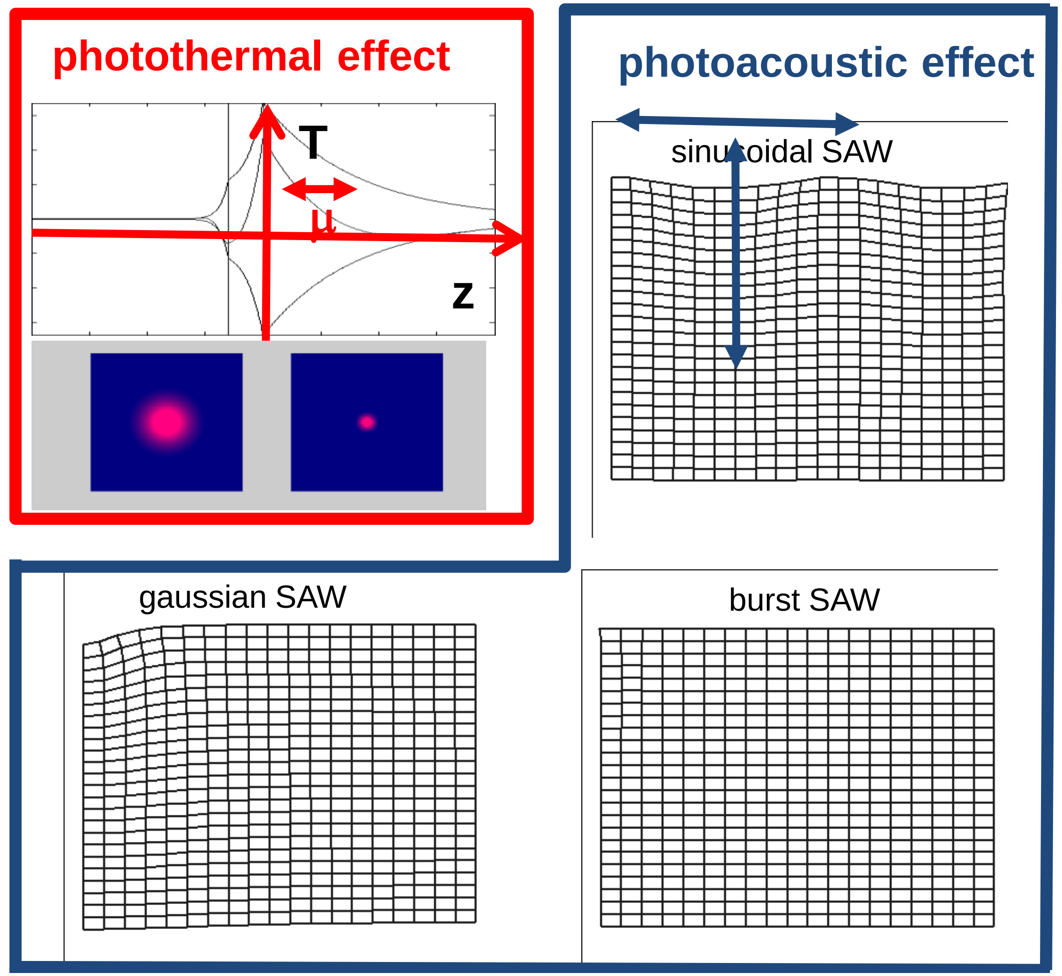


R.B. Bergmann et al., Solar Energy Materials & Solar Cells 74 (2002) 213–218

Photoacoustic and photothermal phenomena: extracting thermal and elastic information from spatial and temporal dependence of temperature and displacement



2D, non-uniform excitation pattern



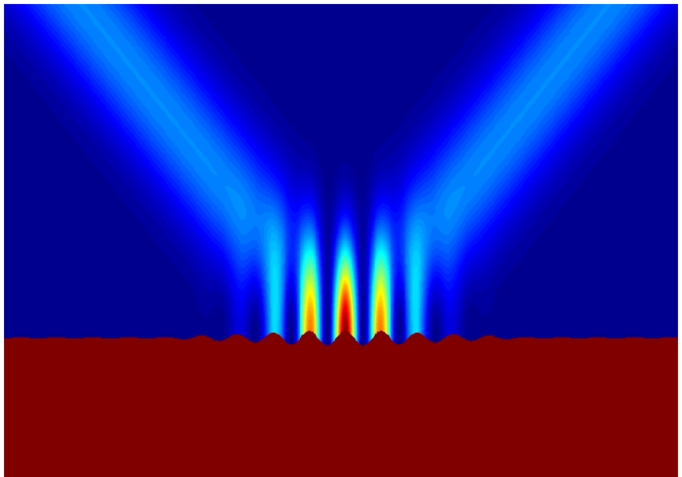
⇒ information on **transport properties**:

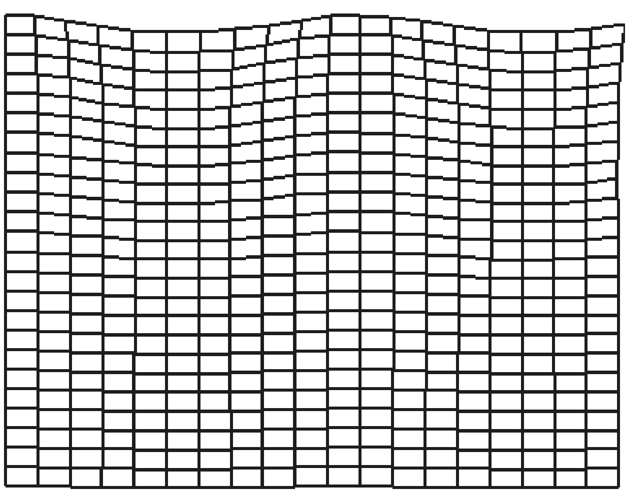
⇒ thermal diffusivity/diffusion length

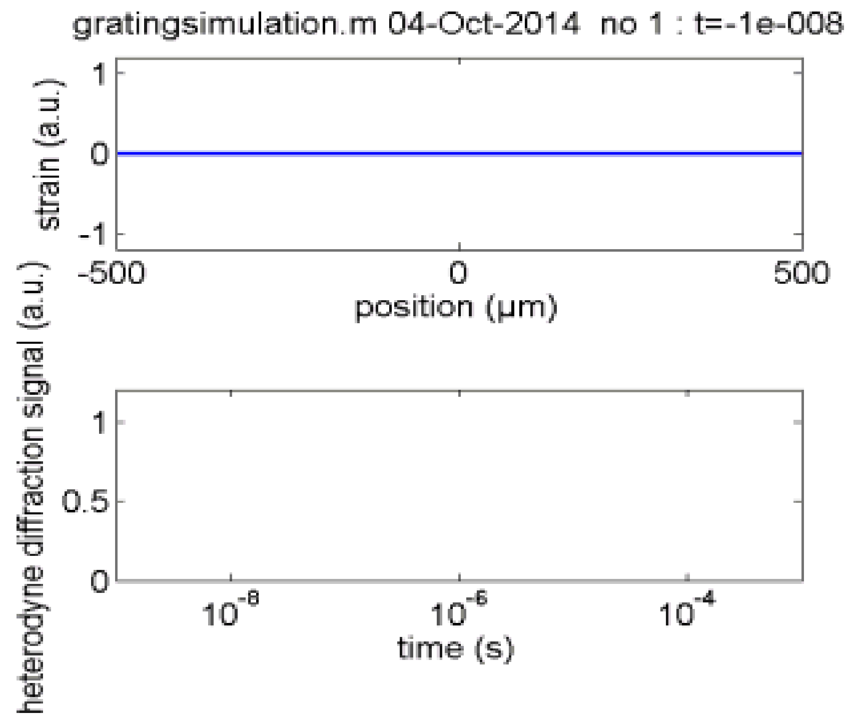
& acoustic velocity and damping/wavelength

Fast and sensitive displacement detection

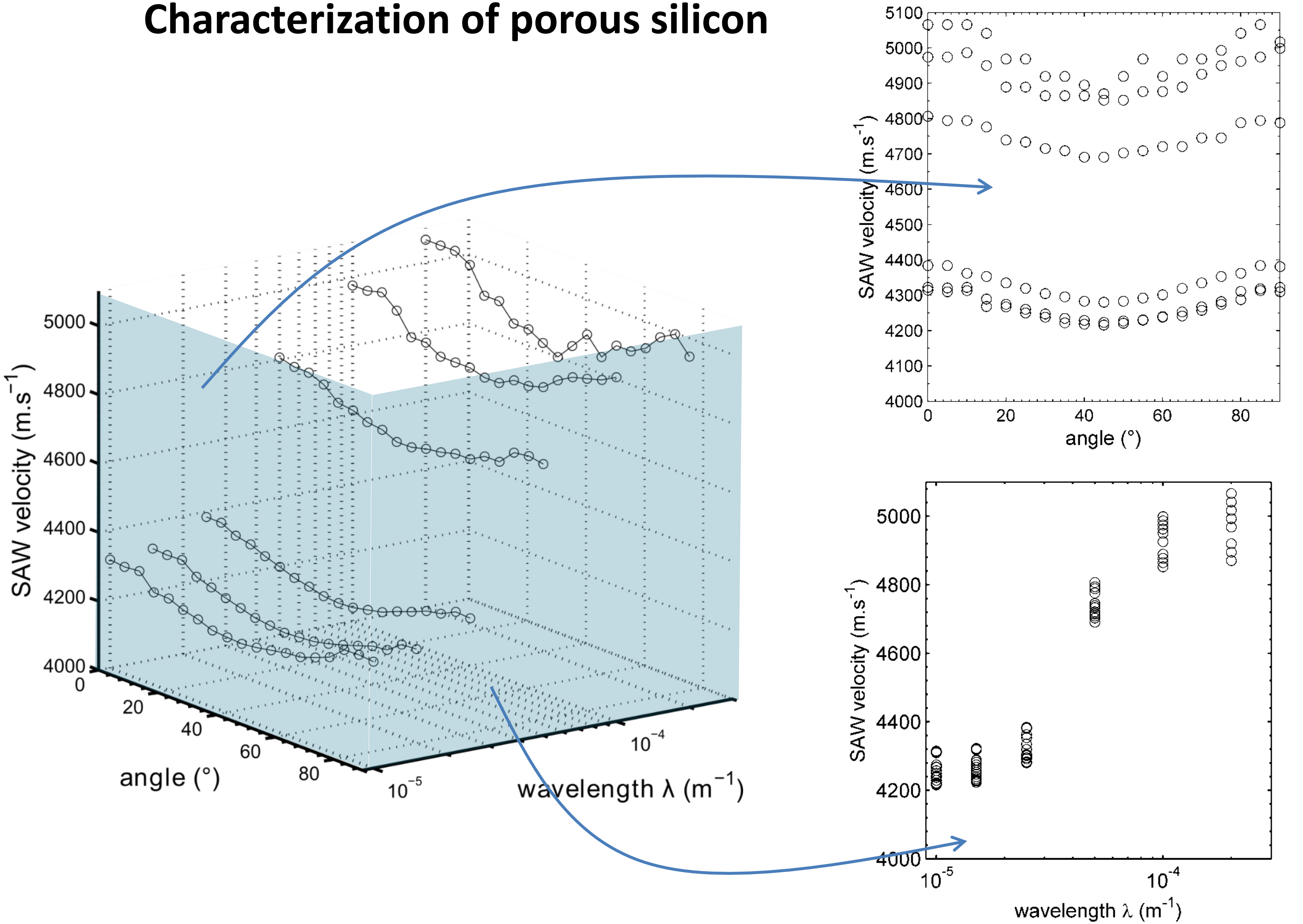
Heterodyne diffraction method



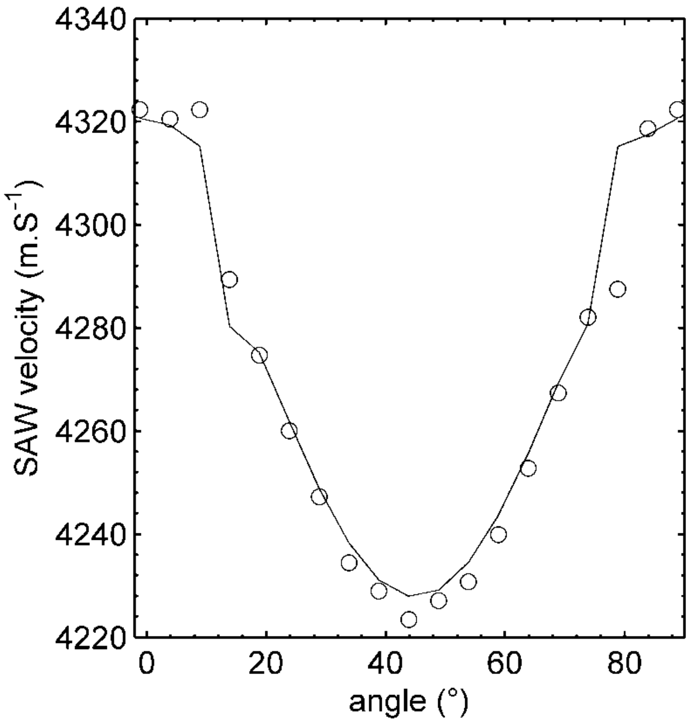


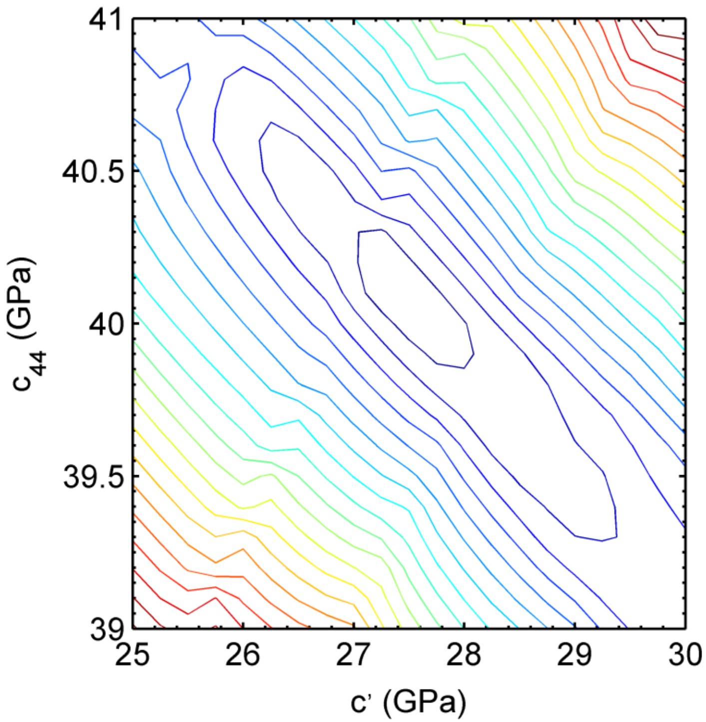


Characterization of porous silicon



Characterization of porous silicon





$$c' = (c_{11}-c_{12})/2 = 27.5 \pm 0.25 \text{ GPa}$$

$$c_{44} = 40.1 \pm 0.1 \text{ GPa}$$

Characterization of porous silicon