



# Implementacja własności warstw bizmutu do zastosowań w giętkiej elektronice

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# Outline

- Motivation
  - Development of flexible magnetic field sensor
    - Investigation of mechanical strain influence
    - Development of optical strain sensor
    - Application of Direct Laser Interference Patterning (DLIP) for optical sensor fabrication
    - Fast temperature measurements for DLIP implementation
- Object of investigations
- Magnetoresistance and Hall sensitivity of pure Bi films
- Influence of mechanical stress and thermoelectric effect on sensor response
- Summary & outlooks



# Motivation

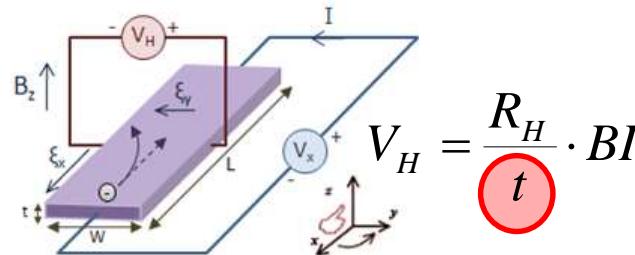


Potential applications:

- Flexible and wearable electronics
- Magnetic bearing systems
- High magnetic field & high frequencies



Why thin film Hall sensor?



$$R_H = \frac{\mu_p - \mu_n}{ne(\mu_p + \mu_n)}$$

Where  $V_H$  – Hall voltage,  
 $R_H$  – Hall resistivity,  $t$  – film thickness,  
 $B$  – magnetic field strength,  
 $I$  – sensor current

[Ref.] E. Ramsden, Hall-Effect Sensors 0750679344 (2006)

Why semimetal?

Johnson noise depends on resistivity

$$V_n = \sqrt{4k_B T \Delta f R}$$

Where  $V_n$  – RMS noise voltage,  
 $k_B$  – Boltzmann constant,  
 $T$  – temperature [K],  
 $\Delta f = f_2 - f_1$  [Hz] – bandwidth,  
 $R$  – resistance of the circuit element.

The best signal-to-noise ratio  
for the Hall sensor can be estimated as

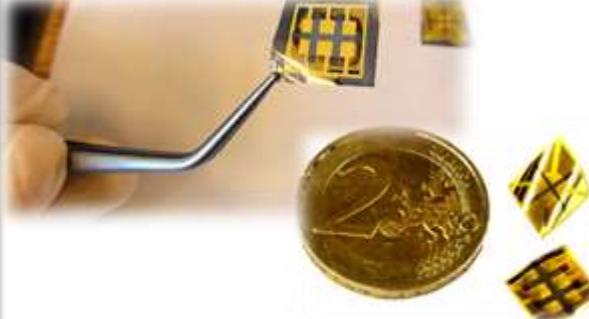
$$\frac{S}{N} = \frac{R_H BI}{t \sqrt{4k_B T R_s}}$$



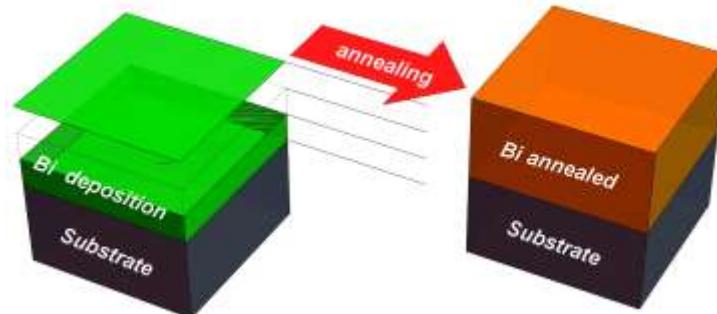
# Object of investigation



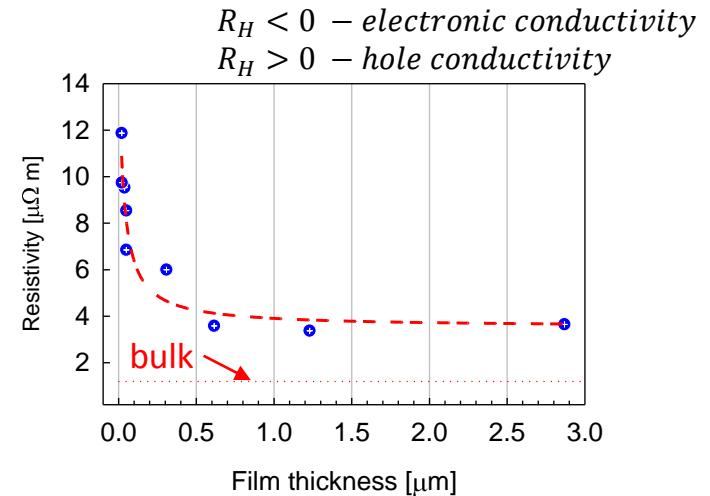
10 $\mu\text{m}$  thick Kapton substrate



Bismuth properties:  
Melting point (bulk): 271.3 °C  
Specific resistance:  $1.29 \times 10^{-6} \Omega \text{ m}$  (@ 20°C)  
Diamagnetic, semimetal  
Effective electron mass:  $\sim 0.001 m_e$   
Mean free path of conductivity electrons can reach  $\lambda \sim 1 \mu\text{m}$



$R_H [\text{cm}^3/\text{C}]$	Reference
-1.77	P. Hofmann, Solid State Physics, 2nd Ed. Wiley-VCH, 2015
-0.1	W. Kobayashi, Appl. Phys. Lett., 100 (1) 2012
-0.05 ... +0.07	M. Boffoué, J. Phys. Chem. Solids, 61 (12) 2000
+0.02 ... +0.05	J. Buxo, Rev. Phys. Appl., 15, 1980
0.09	R. Hoffman, Phys. Rev. B, 3 (6) 1971
0.125	H. Guillou, J. Appl. Phys., 93 (5) 2003
-0.04 ... +0.03	M. Inoue, Appl. Phys., 8 (3) 1975
+0.05 ... +0.1	A. H. de Kuijper, Thin Solid Films, 110 (2) 1983
0.02 ... 0.12	E. I. Rogacheva, Thin Solid Films, 51 (10) 2008
0.07	W. Schnelle, Phys. Status Solidi, 116 (2) 1989
-0.22 ... -0.07	S. A. Stanley, Appl. Phys. A, 120 (4) 2015
-0.5	S. Takabe, Thin Solid Films, 145 (2) 1986
+0.09	L. S. Hsu, J. Appl. Phys., 47 (6) 1976
0.05	L. K. J. Vandamme, Thin Solid Films, 65 (3) 1980
-0.4 ... +0.11	K. S. Wu, Thin Solid Films, 516 (12) 2008
-0.54	C. Kittel, Introduction to Solid State Physics, 8th ed., Wiley 2005

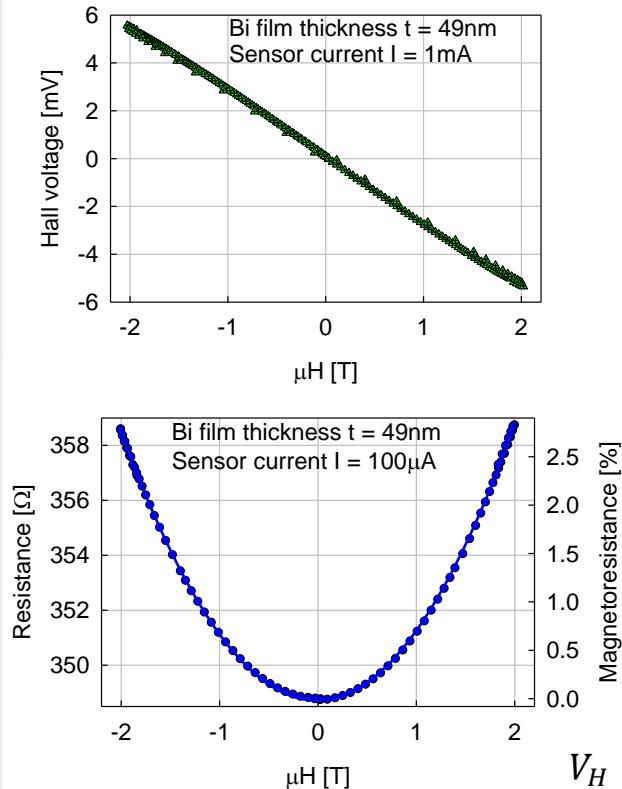




# Hall effect and magnetoresistance

## as-deposited Bi film

[Ref.] Melzer et al., Adv. Mater. 201405027 (2015)



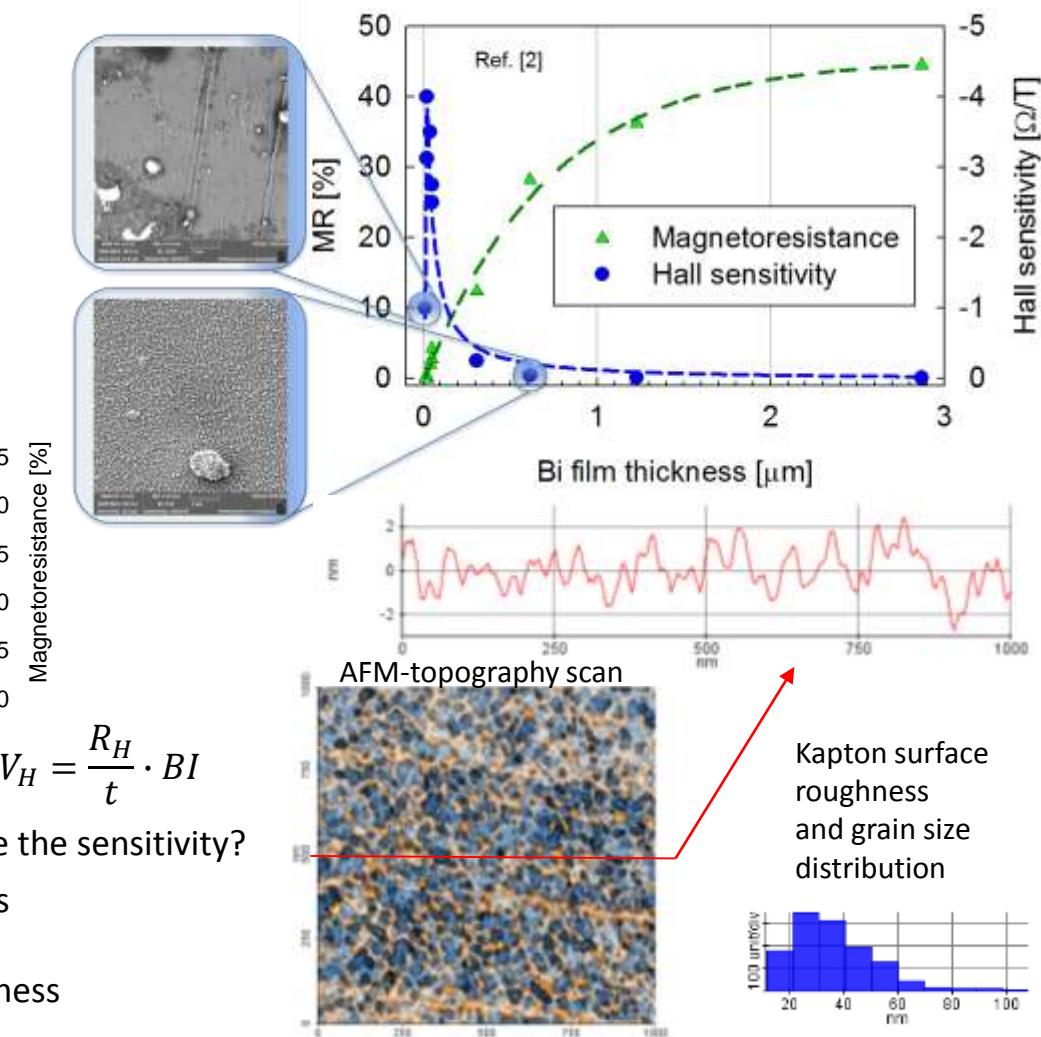
$$V_H = \frac{R_H}{t} \cdot BI$$

How to improve the sensitivity?

$R_H$  - is limited by material properties

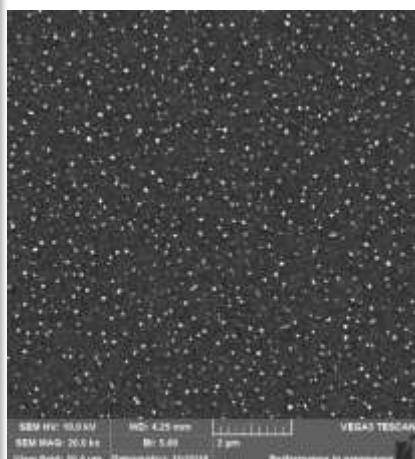
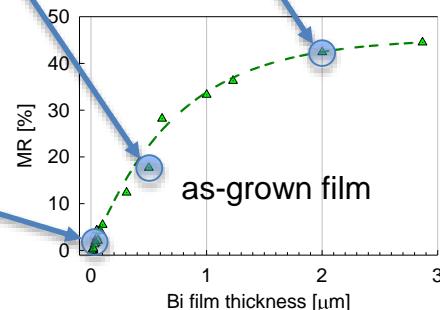
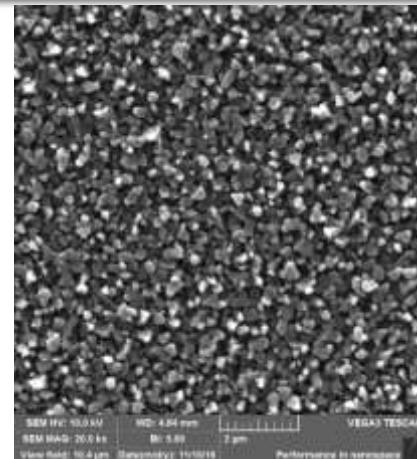
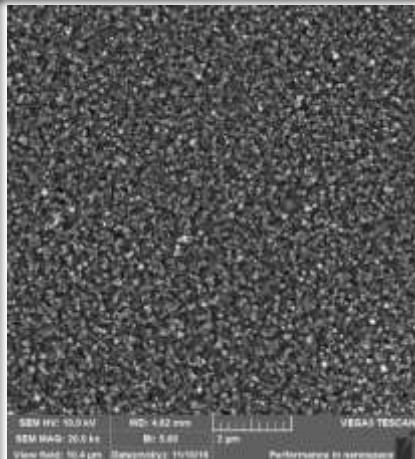
$I$  - is limited by the thermal effects

$t$  - is limited by the substrate roughness



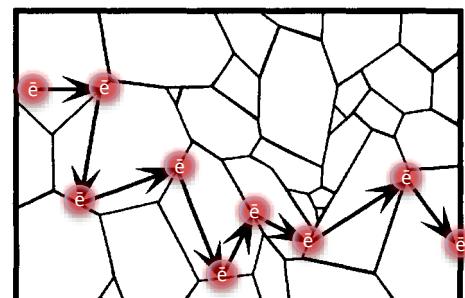


# Magnetoresistance vs film thickness



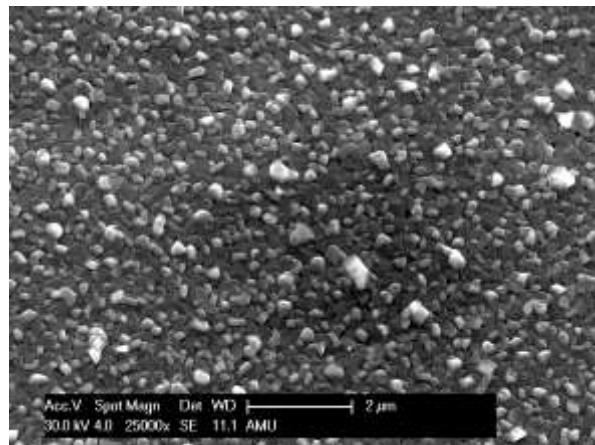
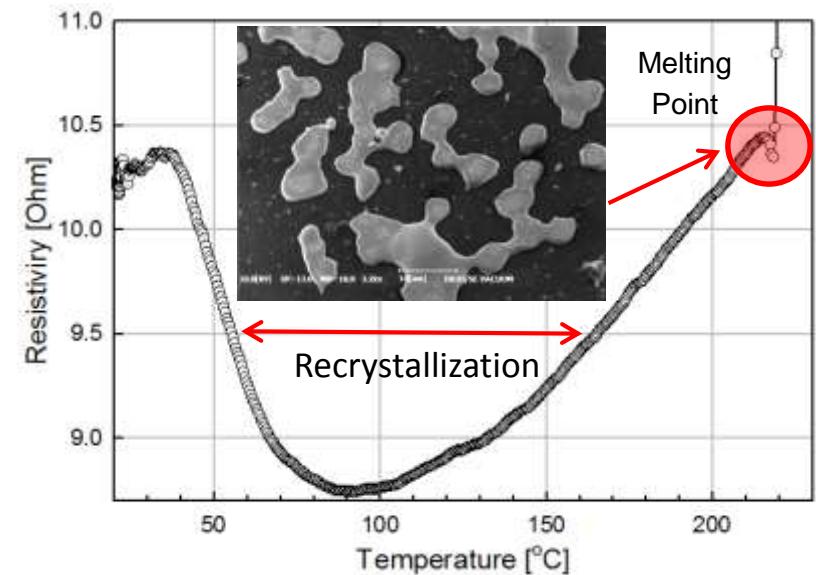
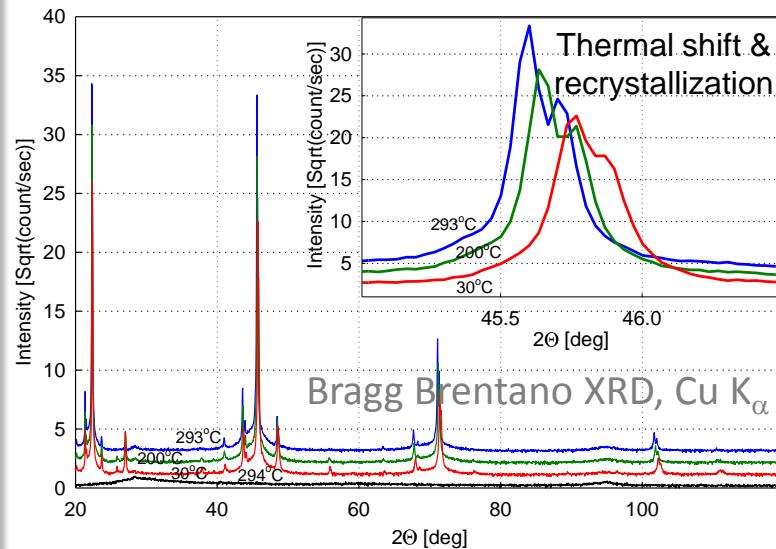
Large magnetoresistance is observed for bigger grains because the charge carriers trajectories are less limited by scattering at grain boundaries and more influenced by magnetic field strength.

Material	Conductivity electron mean free path [nm]	Reference
CVD Graphene	>28µm	Nano Lett. 2016, <b>16</b> , 1387.
Bismuth (Bi)	>1µm	Proc. Phys. Soc A, <b>65</b> (1952) 955. Sov. Phys. JETP, <b>43</b> (3) (1976), 507.
Chromium (Cr)	~1.9nm	JMMM, <b>93</b> (1991) 67.
Iron (Fe)	9.3nm	J L Morán-López „Physics of low dimensional systems (2002). Phys. Stat. Sol. (a) <b>107</b> (1988) 299.
Some other metals	5...54nm	J. Appl. Phys. <b>119</b> (2016), 085101





# Annealing & magnetotransport enhancement

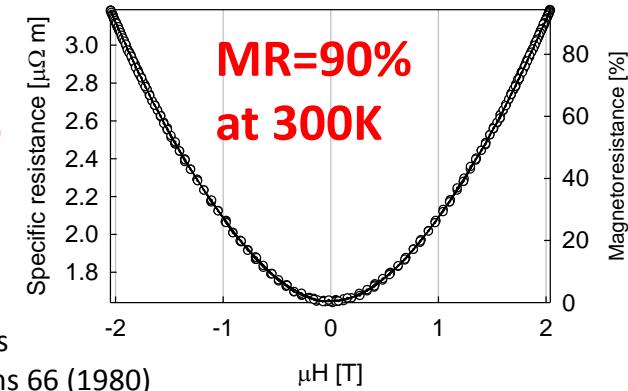


SEM & MR of 1050nm thick film after annealing  
(80h @ 240°C)

$$\frac{\rho - \rho_0}{\rho_0} = \mu_p \mu_n H^2$$

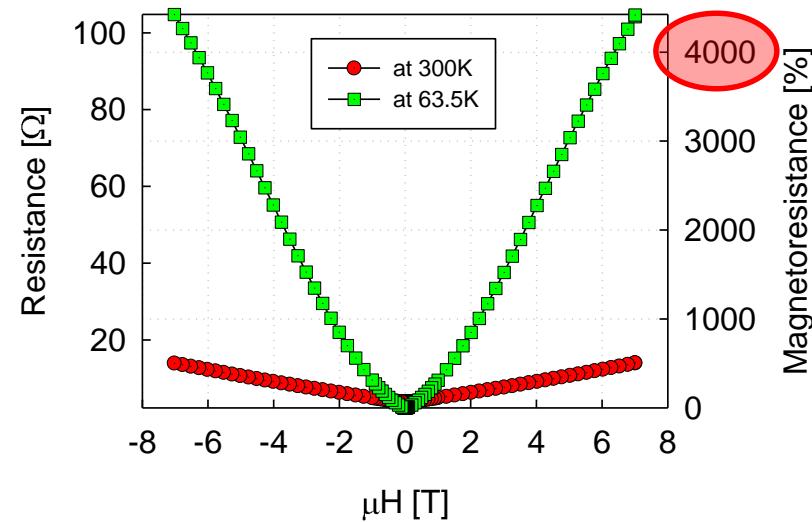
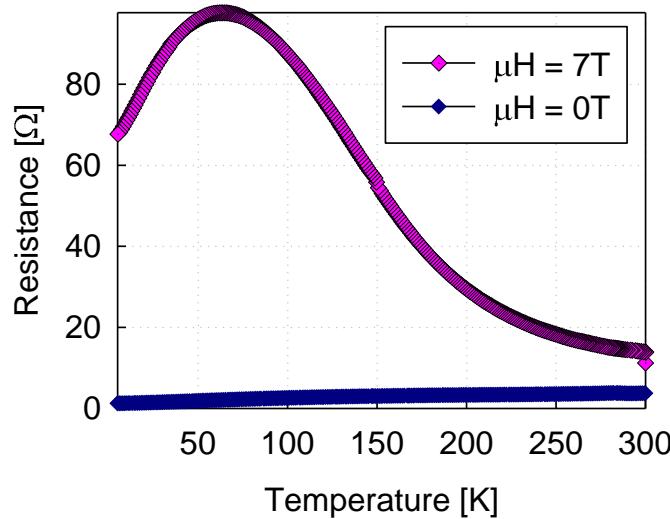
$\rho$ - electrical resistivity  
 $\mu_p$  and  $\mu_n$  are the average hole and electron mobilities

[Ref.] H.Asahi, Thin Sol. Films 66 (1980)





# Magnetoresistance at low temperature and high magnetic field

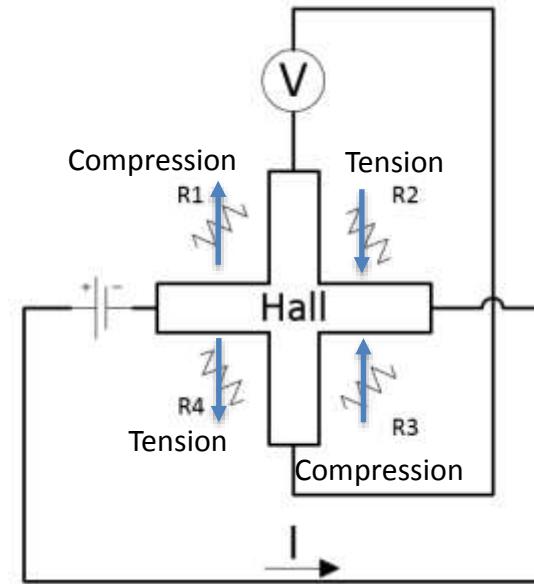
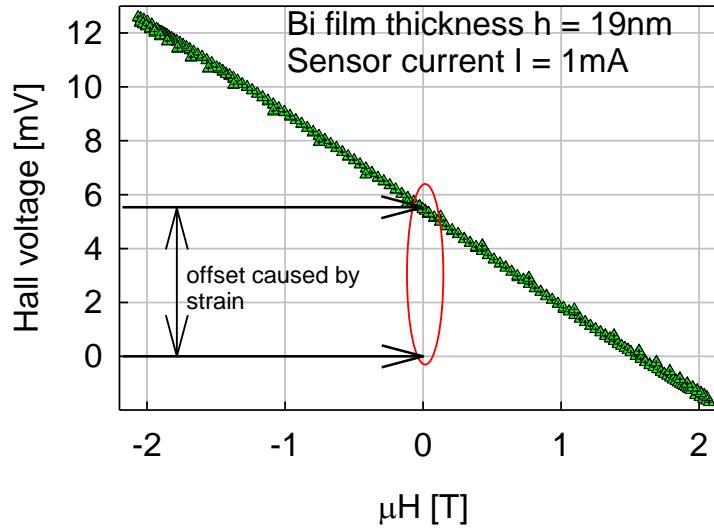


$$\frac{\rho - \rho_0}{\rho_0} = \mu_p \mu_n H^2$$

The significantly enhanced magnetoresistance of Bi layers can be used to design the sensitive magnetic field sensor operating at the cryogenic temperatures and high magnetic fields.



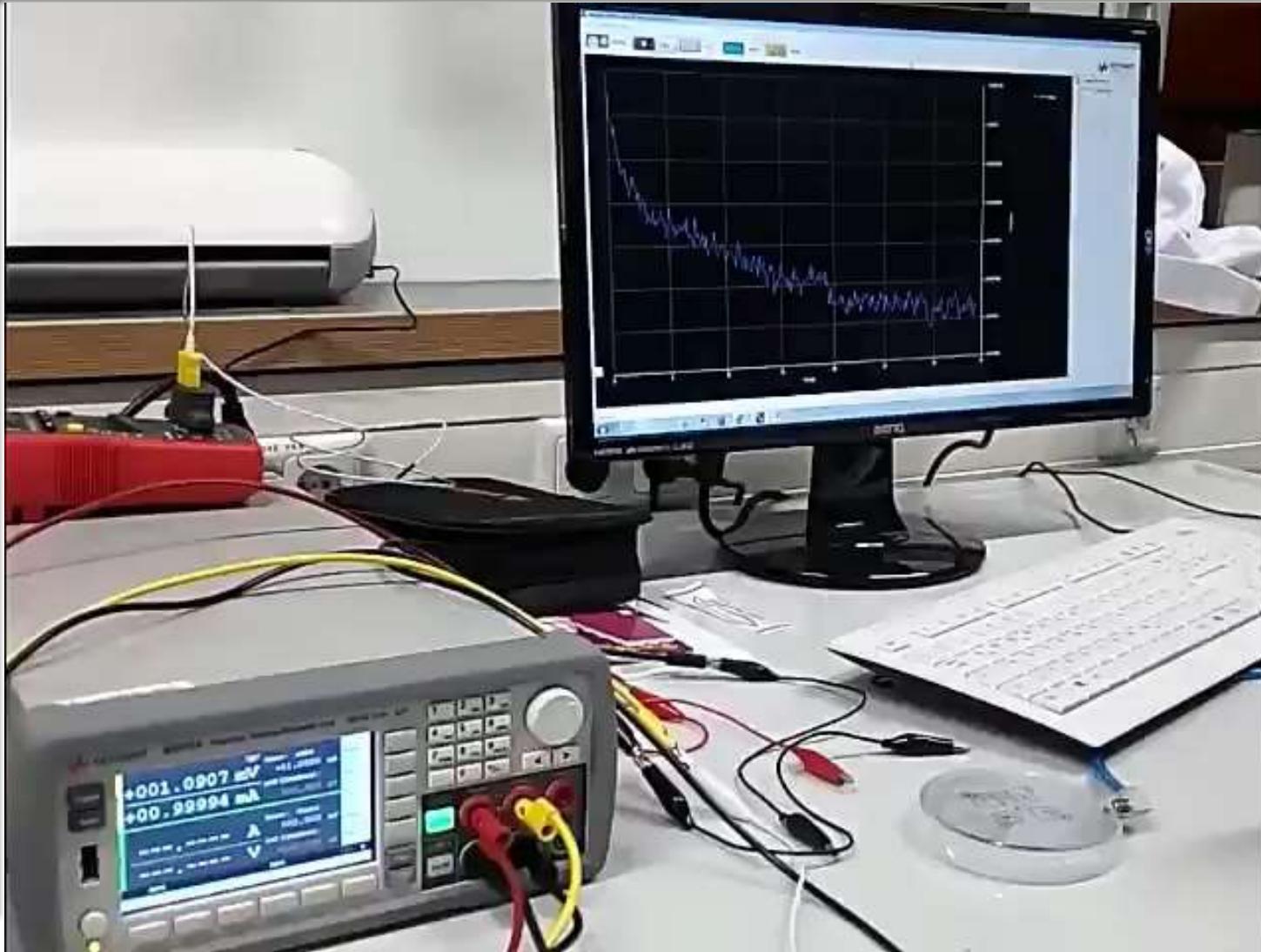
# Mechanical stress influence and Hall offset origin



Flexible Hall sensor acts like a full-bridge strain gauge circuit, generating offset signal coming from non-uniform stress distribution on a polymer substrate. It can be described as a Wheatstone bridge analog.

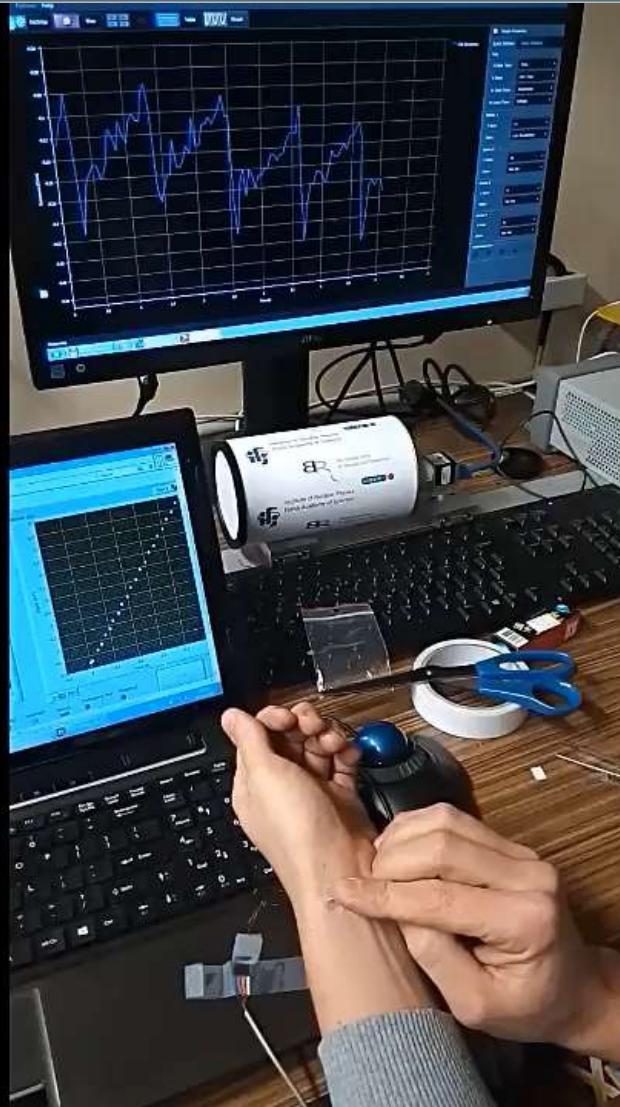


# Mechanical stress influence and Hall offset origin



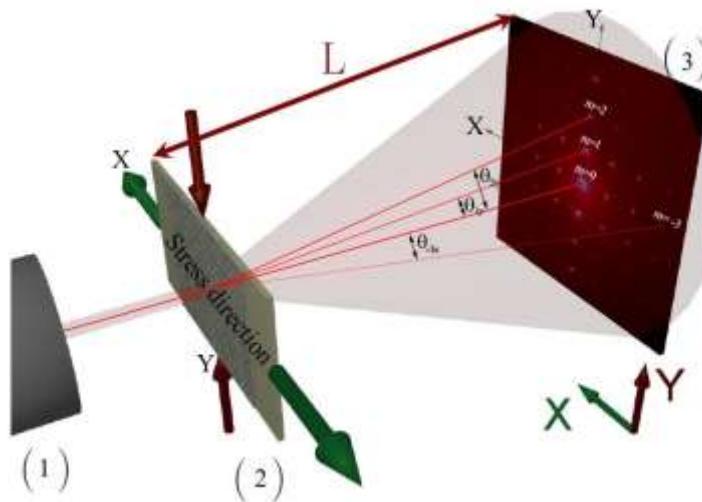


# Mechanical stress influence and Hall offset origin





# Optical strain measurement & Direct Laser Interference Patterning (DLIP)



The schematic presentation of the measurement principle.

1- laser; 2 – diffraction grating; 3 – screen.



## Direct Laser Interference Patterning Setup

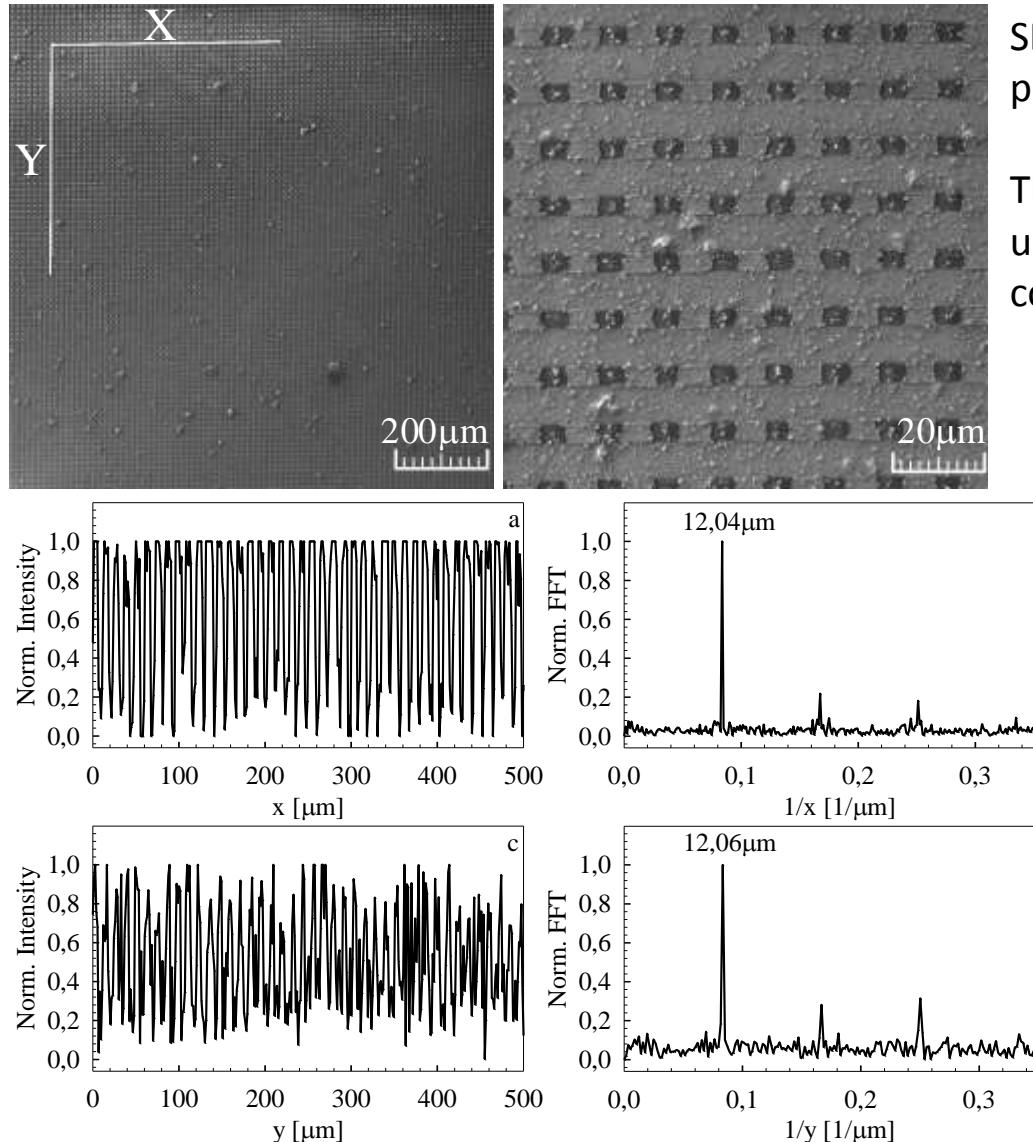
Quantel YG 981E  
Nd:YAG Laser

Linewidth:  $0.003 \text{ cm}^{-1}$  with SLM option  
Energy up to  $1.6 \text{ J}$  @ IR  
 $\lambda = 1064; 532; 355$  and  $266\text{nm}$





# Optical strain sensor prepared by DLIP



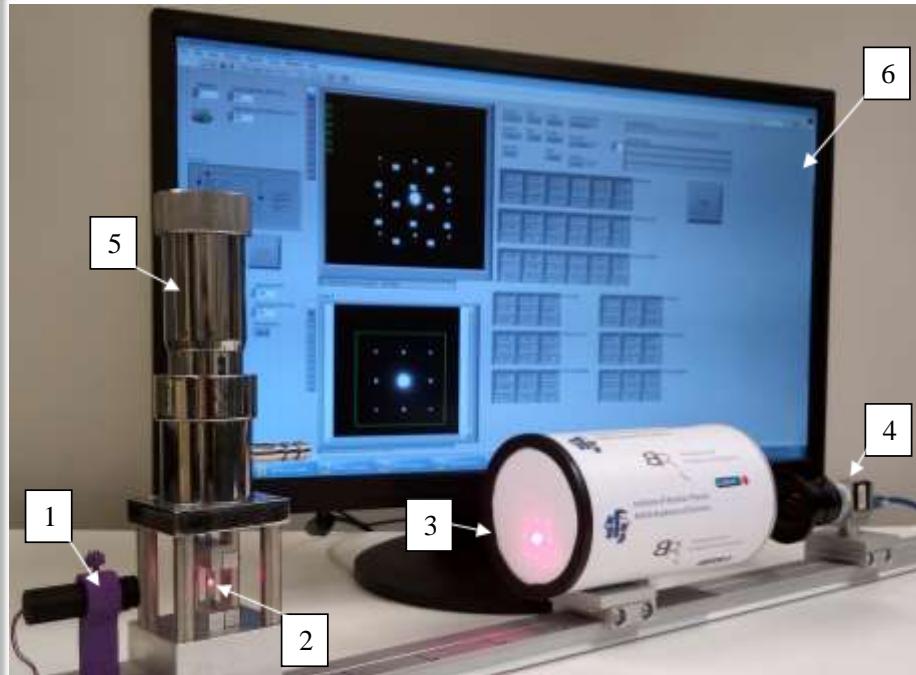
SEM images of diffraction gratings prepared by DLIP method.

The X and Y lines indicate the area used for the estimation of grating constant.

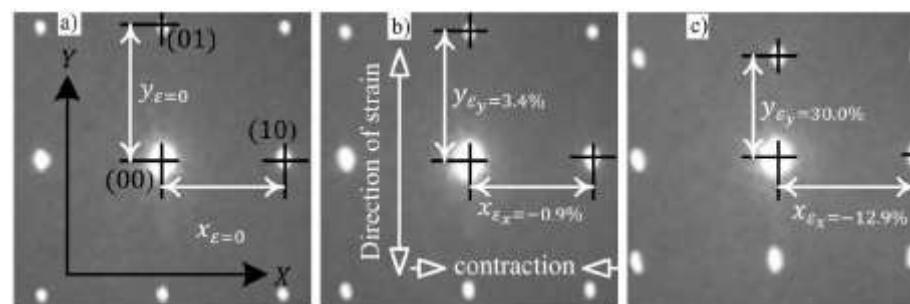
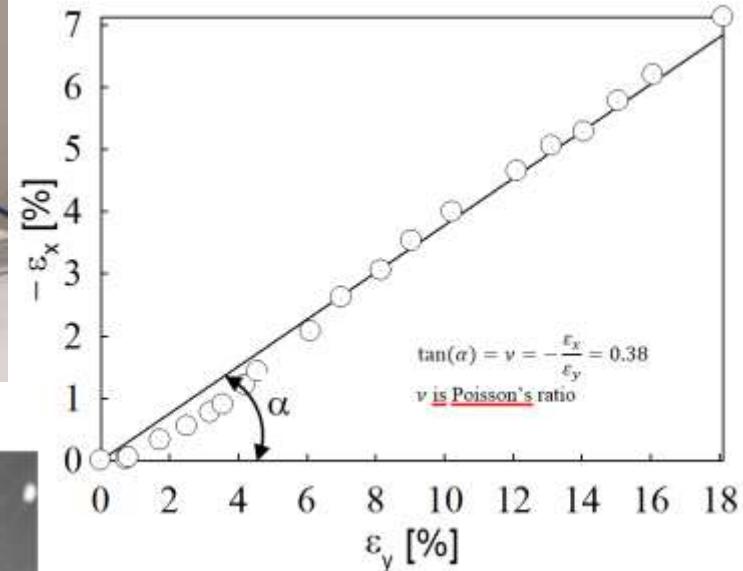
Signal intensity profiles (a, c) of diffraction grating along the X and Y lines and the corresponding Fourier transformation (b, d).



# Optical strain measurements



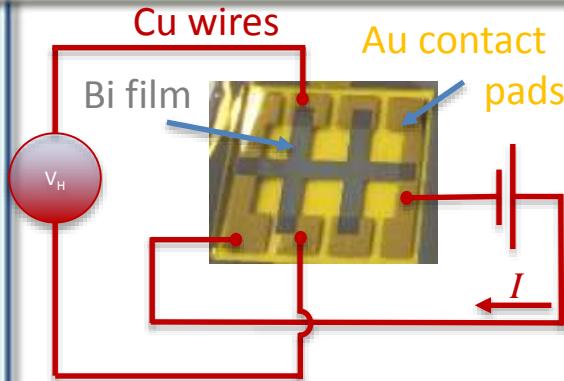
The experimental setup for optical measurements of deformation:  
1 – laser, 2 – diffraction grating,  
3 – semitransparent screen,  
4 – CCD camera, 5 – tensile test device,  
6 – software interface.



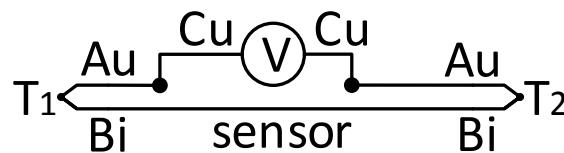
The evolution of the diffraction pattern of grating stretched in the  $y$  direction taken in the transmission mode.

The dependence of  $\varepsilon_x$  on  $\varepsilon_y$  for the diffraction grating with the diffraction constant equal to  $6.3 \mu m$

# Thermoelectric effects



Temperature gradients in the plate result in thermo-voltages and thermal bridge imbalance.



The Seebeck effect gives rise to a potential difference  $V_{AB}$  (thermal offset)

$$V_{Bi-Au} = \int_{T_1}^{T_2} (S_{Bi} - S_{Au}) dT = \int_{T_1}^{T_2} S_{Bi-Au} dT$$

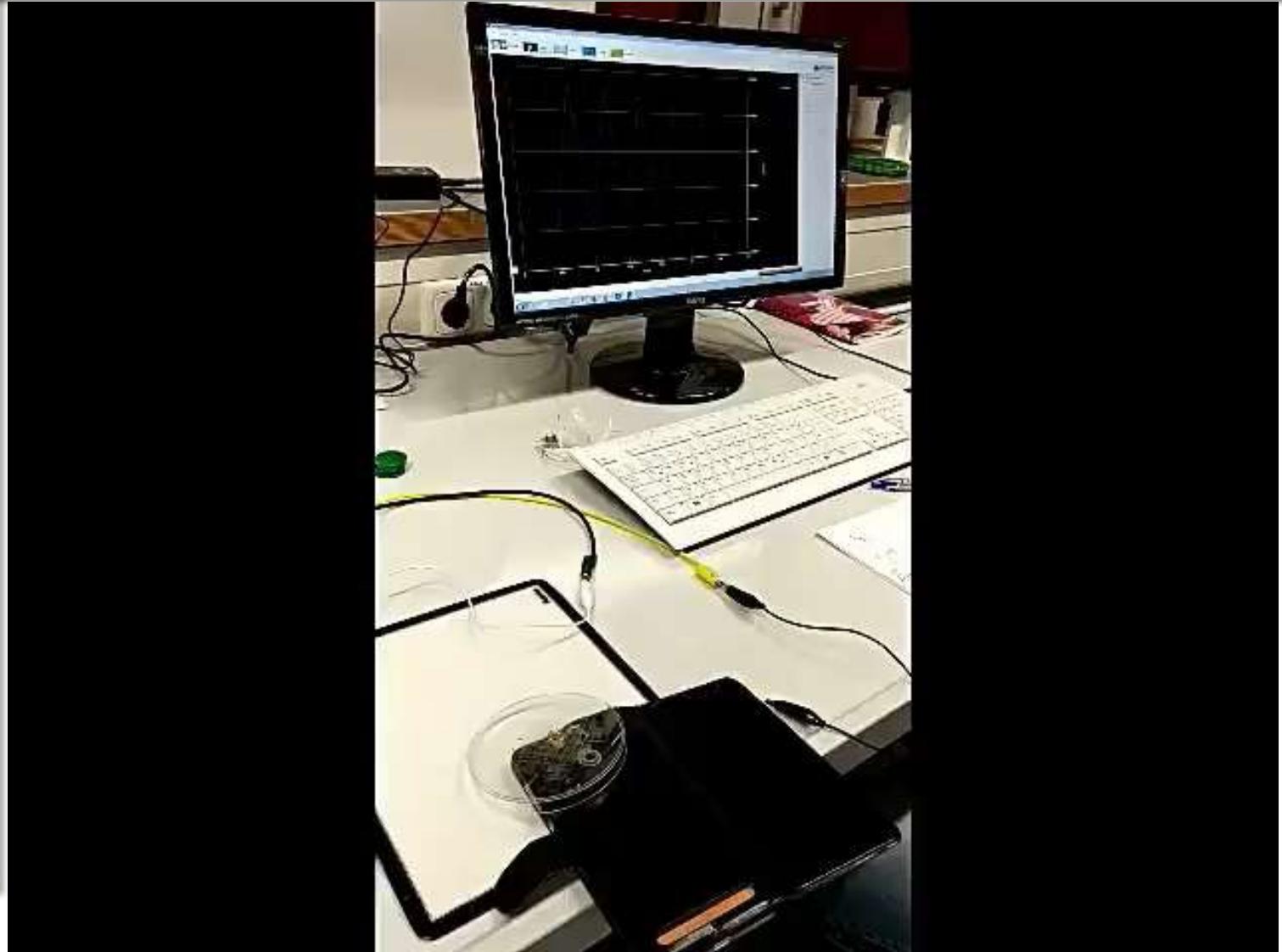
Material	Seebeck coefficient S relative to Platinum [ $\mu\text{V/K}$ ]
Bismuth (Bi)	-72
Nickel	-15
Platinum (Pt)	0
Gold (Au), Silver (Ag), Copper (Cu)	6.5
Silicon (Si)	440
Selenium	900

[https://en.wikipedia.org/wiki/Seebeck\\_coefficient](https://en.wikipedia.org/wiki/Seebeck_coefficient)

Peltier effect creates local temperature gradient on a Kapton surface leading to additional drift of thermal origin which contributes to sensor signal.

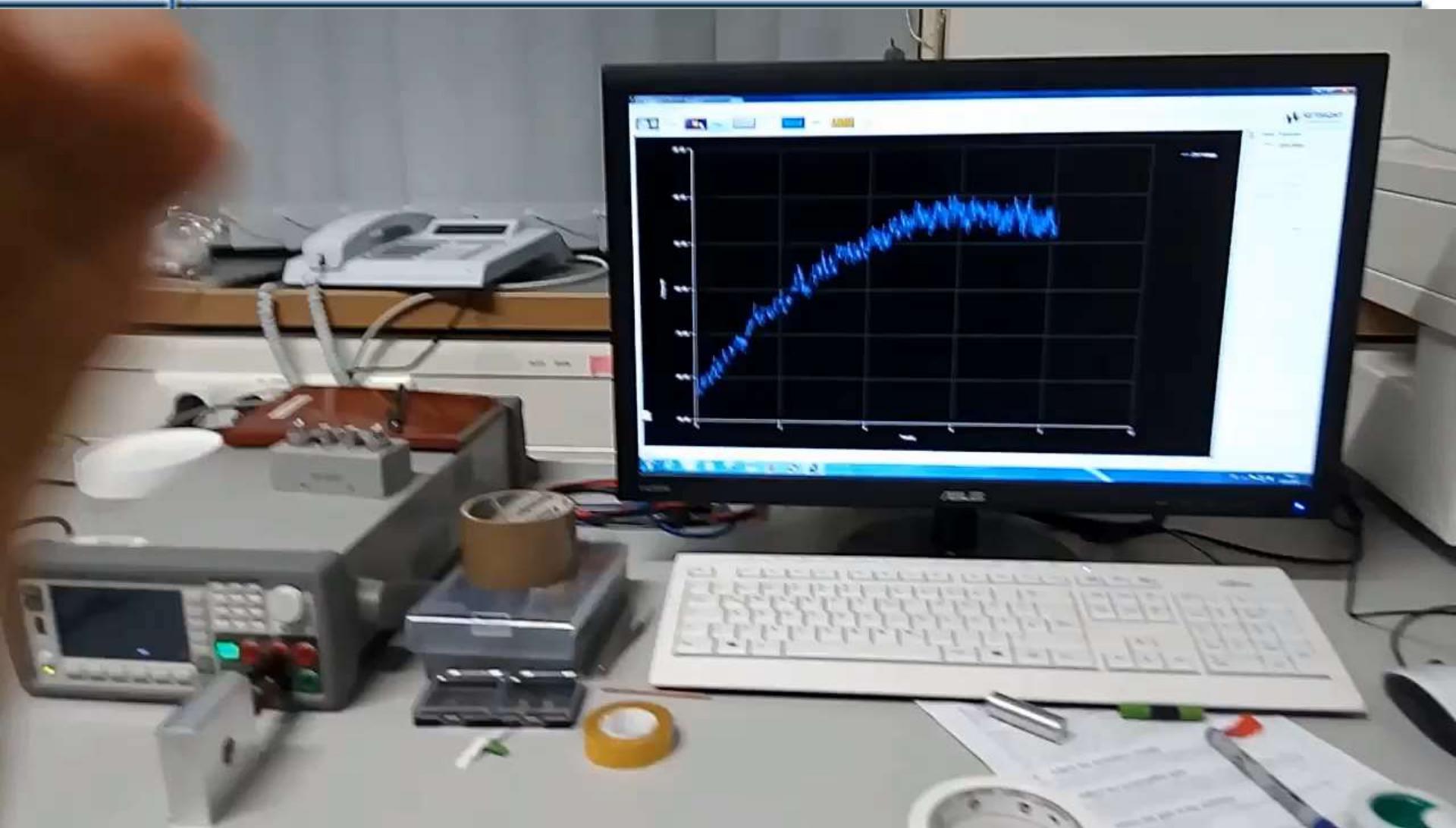


# Thermoelectric effects - light detection



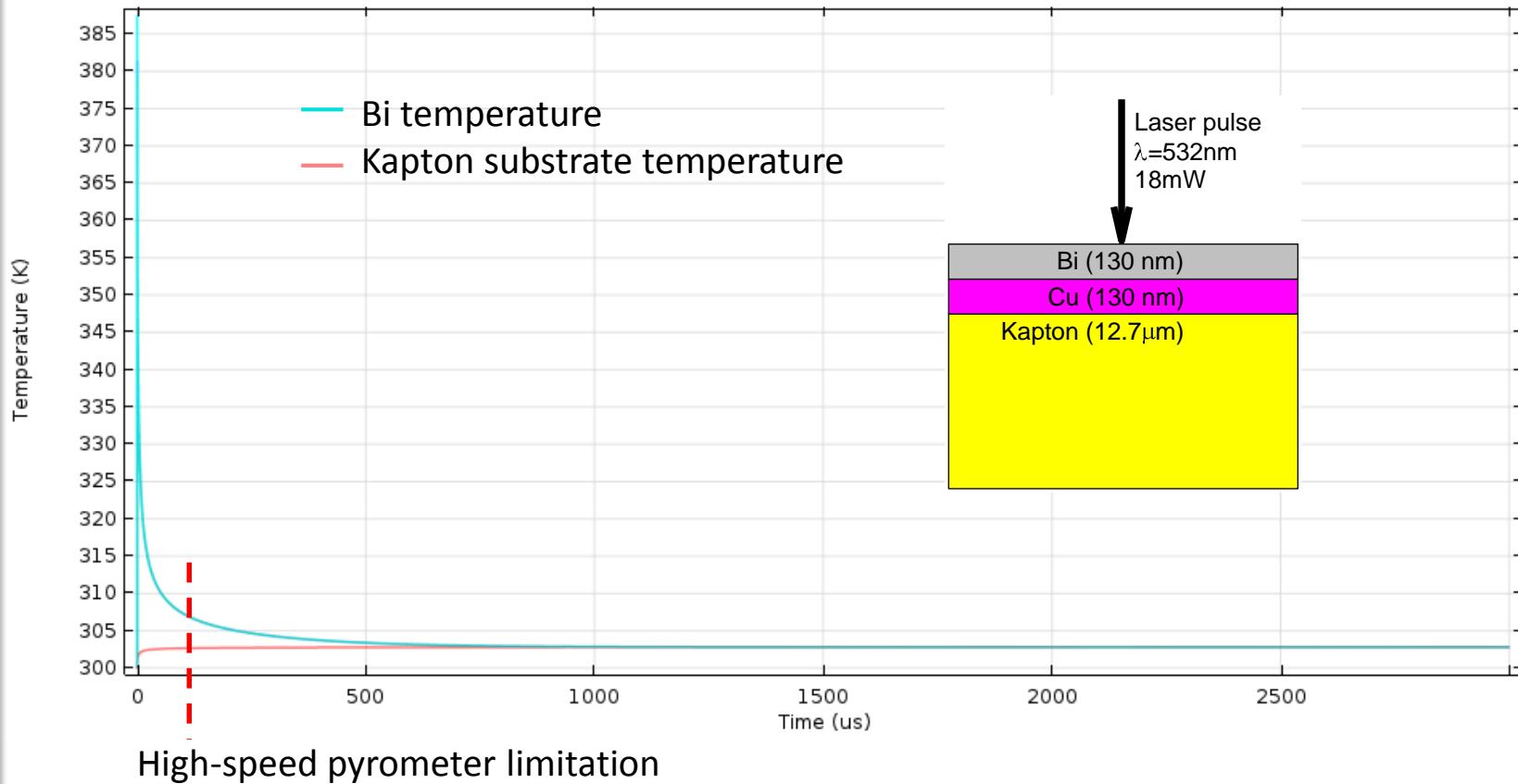


# Thermoelectric effects - IR detector





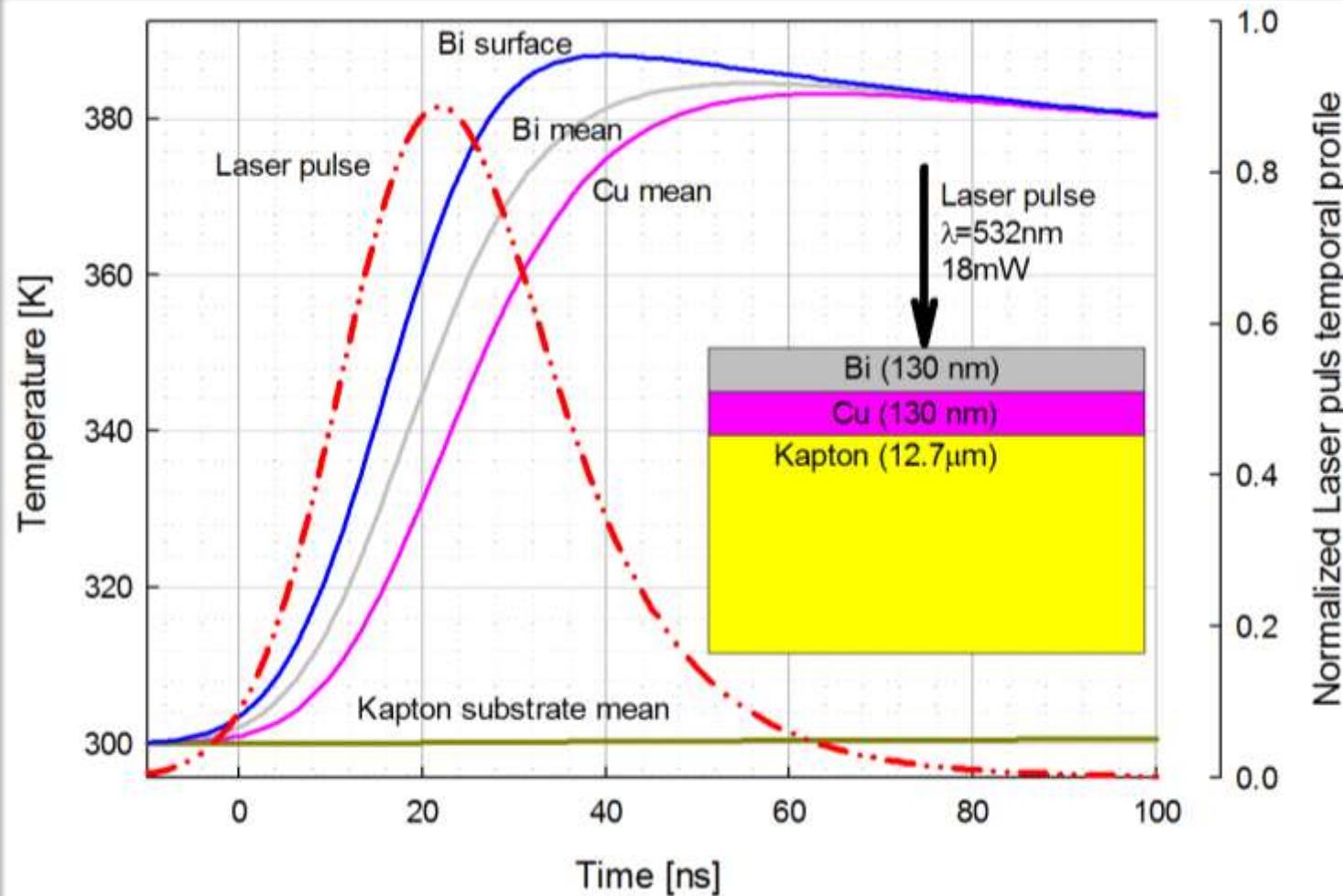
# DLIP and fast temperature measurements



The temperature profile simulated for Bi(130nm)/Cu(130nm)/Kapton thermocouple irradiated with a single 20ns long Nd:YAG pulse.



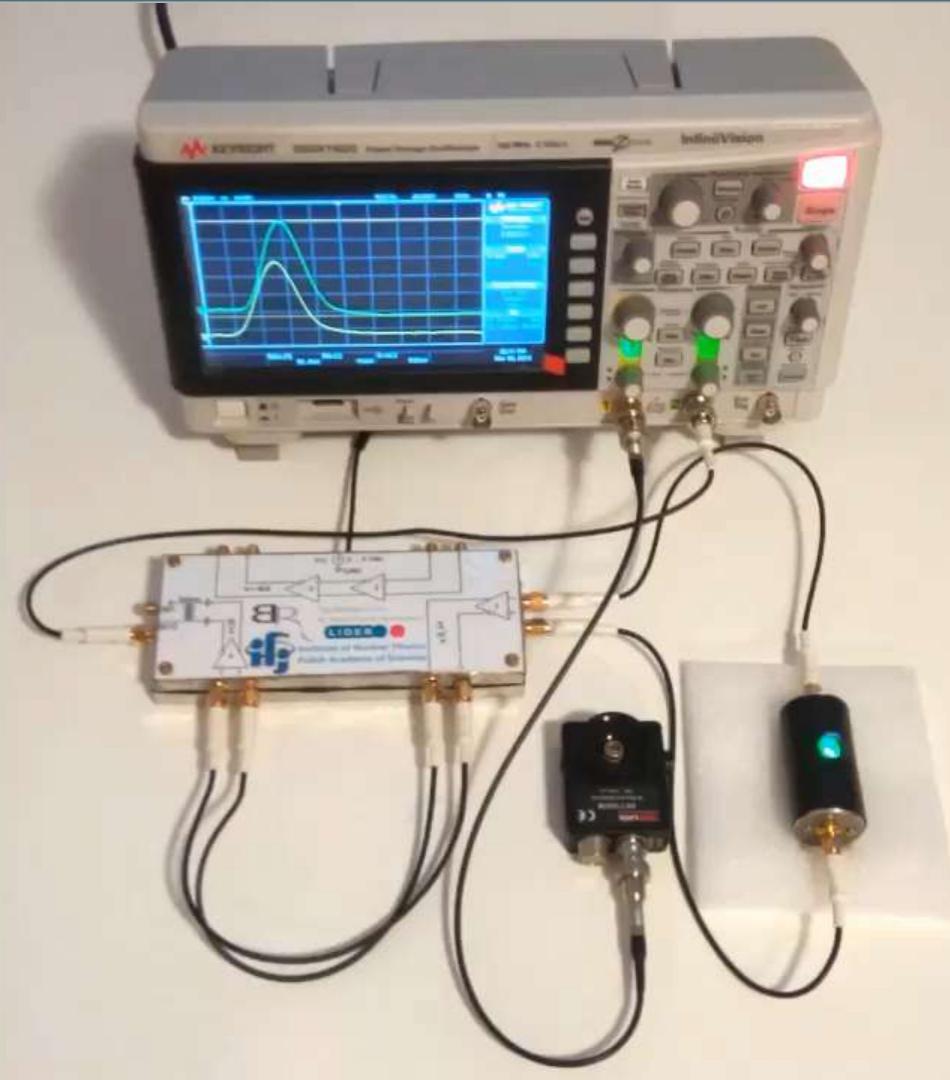
# DLIP and fast temperature measurements



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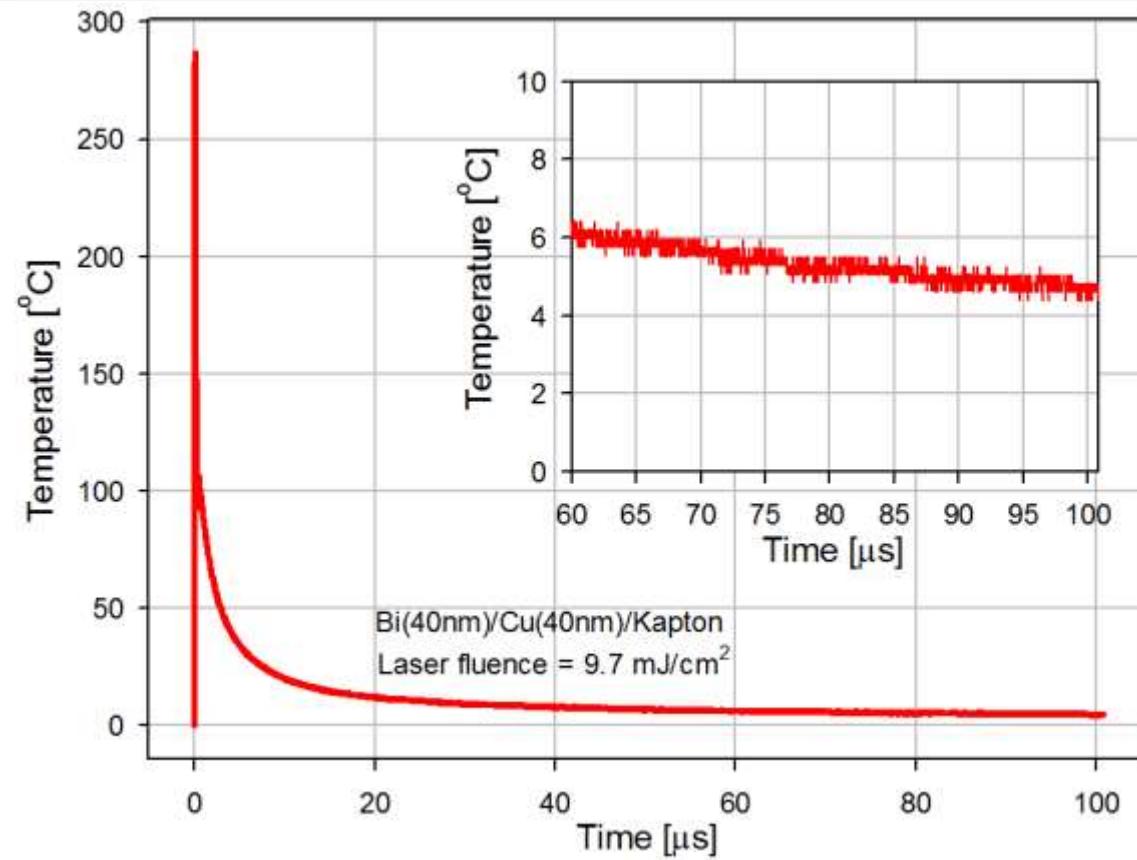


# DLIP and fast temperature measurements





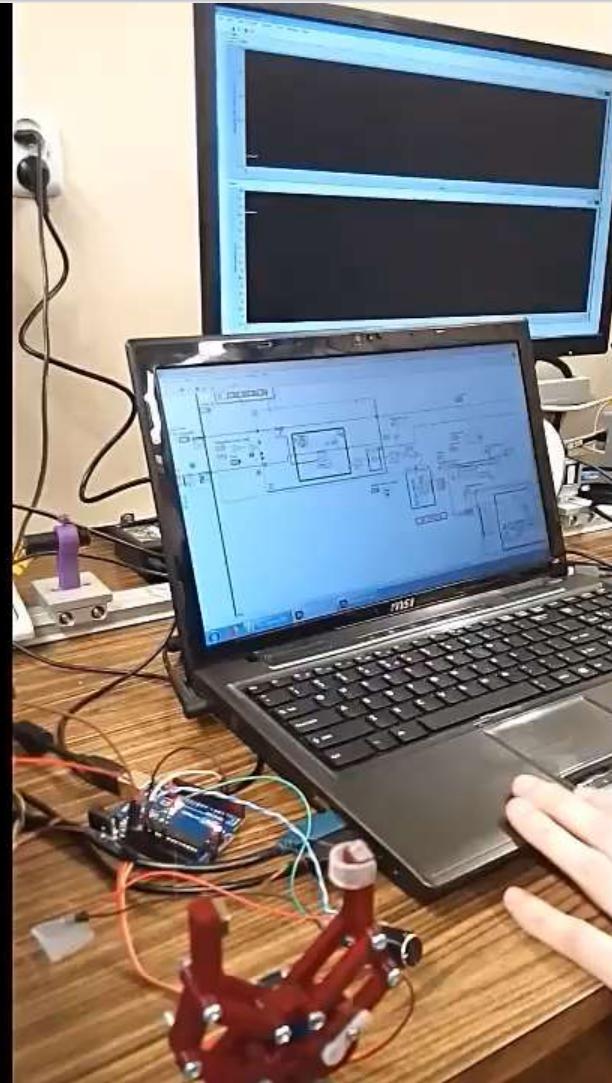
# DLIP and fast temperature measurements



The results of fast temperature measurement for the Bi(40nm)/Cu(40nm)/Kapton layer irradiated with a single laser shot.  
 $\lambda = 532\text{nm}$



# Multifunctional sensor for motion control





# Summary and outlook

- Hall sensitivity decreases with thickness while magnetoresistance increases. It's induced by film morphology.
- The offset in flexible Hall sensors is a result of stress, thermal effects and geometrical imperfections.
- The geometrical imperfections and Seebeck potentials cancel out when the Hall plate is switched orthogonally.
- The 0-offset cancellation techniques allow to measure both magnetic field and strain values by flexible Hall sensor.



# Acknowledgements



This work was supported by the National Centre for Research and Development within LIDER V program, Poland (project Nr.: LIDER/008/177/L-5/13/NCBR/2014).

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