

**UČNI NAČRT PREDMETA / COURSE SYLLABUS**

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|----------------------|--|
| <b>Predmet:</b>      | Lokalne električne, elektromehanske in termične lastnosti senzorskih materialov    |
| <b>Course title:</b> | Local Electrical, Electromechanical and Thermal Properties of the Sensor Materials |

| Študijski program in stopnja<br>Study programme and level | Študijska smer<br>Study field | Letnik<br>Academic year | Semester<br>Semester |
|---|-------------------------------|-------------------------|----------------------|
| Senzorske tehnologije, 3. stopnja                         | /                             | 1                       | 1                    |
| Sensor Technologies, 3 <sup>rd</sup> cycle                | /                             | 1                       | 1                    |

**Vrsta predmeta / Course type** Izbirni / Elective

**Univerzitetna koda predmeta / University course code:** ST3-652

| Interaktivna predavanja<br>Lectures | Seminar<br>Seminar | Vaje<br>Tutorial | Klinične vaje<br>work | Druge oblike študija | Samost. delo<br>Individ. work | ECTS |
|-------------------------------------|--------------------|------------------|-----------------------|----------------------|-------------------------------|------|
| 15                                  | 15                 |                  |                       | 15                   | 105                           | 5    |

*\*Navedena porazdelitev ur velja, če je vpisanih vsaj 10 študentov. Drugače se obseg izvedbe kontaktnih ur sorazmerno zmanjša in prenese v samostojno delo. / This distribution of hours is valid if at least 10 students are enrolled. Otherwise the contact hours are linearly reduced and transferred to individual work.*

**Nosilec predmeta / Lecturer:** Doc. dr. Hana Uršič

**Jeziki / Predavanja / Lectures:** Slovenščina, angleščina / Slovenian, English  
**Languages: Vaje / Tutorial:** Slovenščina, angleščina / Slovenian, English

**Pogoji za vključitev v delo oz. za opravljanje študijskih obveznosti:**

Zaključen študij druge stopnje ustrezne (naravoslovne ali tehniške) smeri ali zaključen študij drugih smeri z dokazanim osnovnim znanjem področja predmeta (pogovor, pisna dokazila).

**Prerequisites:**

Completed second cycle studies in natural sciences or engineering or completed second cycle studies in other fields with proven knowledge of fundamentals in the field of this course (interview, documentation).

**Vsebina:**

- Aktualne tehnološke rešitve in metode za merjenje lokalnih električnih, elektromehanskih in termičnih lastnosti funkcijskih materialov
- Osnovni principi delovanja mikroskopa na atomsko silo (AFM) s piezoelektričnim (PFM), prevodnim (CAFM) in temperaturnim (SThM) modulom ter ostale sorodne tehnike
- Napredne merilne tehnike na osnovi AFM, kot na primer tehnika za določanje lokalnih elektrokaličnih lastnosti na osnovi modificiranega SThM sistema

**Content (Syllabus outline):**

- Up-to-date technological solutions and methods for determination of local electrical, electromechanical and thermal properties of functional materials
- Basic principles of atomic force microscopy (AFM), piezo-force microscopy (PFM), conductive-force microscopy (CAFM), scanning thermal microscopy (SThM) and related techniques
- Advanced measurement techniques based on AFM, such as determination of local

- Povezave med lokalnimi in makroskopskimi lastnostmi funkcijskih materialov
- Individualno poglobljena analiza izbranega realnega primera iz študentove disertacije:
  - I) izbor primerne tehnike za določitev želenih lokalnih lastnosti (kot na primer lokalne električne prevodnosti, lokalnega piezoelektričnega odziva, feroelektrične domenske strukture, nukleacija in preklapanje domen, lokalna toplotna prevodnost, itd.),
  - II) eksperimentalno delo na mikroskopu ter analiza dobljenih rezultatov.

electocaloric properties by modified SThM system

- Connections between the local and macroscopic properties of the functional materials.
- Individual analysis of a case study related to the topic of the student's PhD research:
  - I) selection of a suitable technique for the determination of local target properties (such as local electrical conduction, local piezoelectric response, ferroelectric domain structure, domain nucleation and switching, local thermal conductivity, etc.),
  - II) practical work on the microscope and analysis of measured results.

### Temeljni literatura in viri / Readings:

Izbrani članki predvsem v revijah Nature, Science, Advanced Functional Materials, Sensors and Actuators, Physical Review Letters, Acta Materialia / Targeted selection of papers from Nature, Science, Advanced Functional Materials, Sensors and Actuators, Physical Review Letters, Acta Materialia.

S. Kalinin, A. Gruverman, Scanning probe microscopy, Electrical and electromechanical phenomena at the nanoscale, 2007, Springer Science+Business Media, LLC.

### Cilji in kompetence:

#### Cilji predmeta so:

- študent se seznanja s koncepti in opremo za določanje lokalnih električnih, elektromehanskih in toplotnih lastnosti različnih senzorskih materialov;
- študent spozna osnovne principe delovanja AFM, PFM, CAFM in SThM ter ostale sorodne tehnike, kot so AFM s Kelvinovo sondo (KPFM), mikroskopija električnih sil (EFM) in mikroskopija magnetnih sil (MFM);
- študent izmeri in analizira lokalne lastnosti senzorskih materialov (kratak raziskovalni projekt).

#### Kompetence študenta:

- izbere primerno tehniko za določanje želenih lokalnih lastnosti,
- zna pripraviti vzorce (npr. kristale, volumenske materiale, tanke in debele plasti, nanomaterialne, itd.) za meritve lokalnih lastnosti,
- določi in analizira želene lokalne lastnosti senzorskega materiala, kot so na primer lokalna električna prevodnost, lokalni piezoelektrični odziv, feroelektrična domenska

### Objectives and competences:

#### The objectives of the course are:

- student becomes familiar with the concepts of and equipment for determination of local electrical, electromechanical and thermal properties of different sensor materials.
- student understands basic principles of AFM, PFM, CAFM, SThM and other related techniques such as Kelvin-probe force microscopy (KPFM), electrostatic-force microscopy (EFM) and magnetic-force microscopy (MFM)
- student measures and analyses selected material's characteristics (a short research project).

#### Competences of the student:

- Ability to select appropriate technique for desired local measurements.
- Ability to prepare the samples (for example crystals, bulk materials, thin and thick films, nanomaterials, etc.) for microscopic analyses of local properties.
- Ability to determine and analyse selected material's characteristics such as local electrical conduction, local piezoelectric behaviour, ferroelectric domain structure, local thermal

struktura, lokalna toplotna prevodnost, itd.,

- zna povezati lokalne in makroskopske lastnosti materialov

properties, etc.

- Ability to understand the connections between the local and macroscopic properties of materials.

#### Predvideni študijski rezultati:

Znanje in razumevanje:

- Razumevanje osnov lokalnih električnih, elektromehanskih in termičnih lastnosti senzorskih materialov.
- Poznavanje AFM, PFM, CAFM, SThM in sorodnih tehnik.
- Sposobnost povezovanja znanj o AFM tehnikah in praktičnega dela na mikroskopu pri analizi konkretnega primera v okviru doktorskega študija.

#### Intended learning outcomes:

Knowledge and understanding:

- Understanding the principles of local electrical, electromechanical and thermal properties of different sensor materials.
- Knowledge of AFM, PFM, CAFM, SThM and related techniques.
- Ability to correlate knowledge and skills of advanced AFM techniques to perform practical exercise on the microscope related to the PhD research.

#### Metode poučevanja in učenja:

Interaktivna predavanja.  
Individualno voden študij, ki vključuje vodeno praktično delo na mikroskopu in predstavitev rezultatov v obliki seminarske naloge.

#### Learning and teaching methods:

Interactive lectures.  
Individually guided study which includes guided practical work on the microscope related to the PhD research and presentation of results in a seminar form.

Delež (v %) /

Weight (in %)

#### Načini ocenjevanja:

#### Assessment:

|  |      |  |
|--|------|--|
| Seminarska naloga, ki vsebuje teorijo in rezultate praktičnih vaj na mikroskopu. | 50 % | Seminar, which includes the theory as well as results of practical exercise on the microscope. |
| Ustni izpit.   | 50 % | Oral exam.   |

#### Reference nosilca / Lecturer's references:

1. URŠIČ, Hana, RICOTE, Jesús, AMORÍN, Harvey, HOLC, Janez, KOSEC, Marija, ALGUERÓ, Miguel. Ferroelectric domain configurations in 0.65Pb(Mg<sub>1/3</sub>Nb<sub>2/3</sub>)O<sub>3</sub>-0.35PbTiO<sub>3</sub> thick films determined by piezoresponse force microscopy. *Journal of physics. D, Applied physics*, 2012, vol. 45, no. 26, str. 265402-1-265402-11, [COBISS.SI-ID [25895463](#)]
2. ROJAC, Tadej, URŠIČ, Hana, BENČAN, Andreja, MALIČ, Barbara, DAMJANOVIĆ, Dragan. Mobile domain walls as a bridge between nanoscale conductivity and macroscopic electromechanical response. *Advanced functional materials*, 2015, vol. 25, no. 14, str. 2099-2108 [COBISS.SI-ID [28359975](#)]
3. KUPEC, Alja, URŠIČ, Hana, FRUNŽA, Raluca-Camelia, TCHERNYCHOVA, Elena, MALIČ, Barbara. Microstructure-dependent leakage-current properties of solution-derived (K<sub>0.5</sub>Na<sub>0.5</sub>)NbO<sub>3</sub> thin films. *Journal of the European ceramic society*, 2015, vol. 35, no. 13, str. 3507-3511 [COBISS.SI-ID [28709927](#)]
4. URŠIČ, Hana, DRNOVŠEK, Silvo, MALIČ, Barbara. Complex domain structure in polycrystalline Pb(Sc<sub>0.5</sub>Nb<sub>0.5</sub>)O<sub>3</sub>. *Journal of physics. D, Applied physics*, ISSN 0022-3727, 2016, vol. 49, str. 115304-1-115304-4, [COBISS.SI-ID [29301543](#)]
5. ROJAC, Tadej, BENČAN, Andreja, DRAŽIĆ, Goran, SAKAMOTO, Naonori, URŠIČ, Hana, JANČAR, Boštjan, TAVČAR, Gašper, MAKAROVIČ, Maja, WALKER, Julian, MALIČ, Barbara, DAMJANOVIĆ, Dragan. Domain-wall conduction in ferroelectric BiFeO<sub>3</sub> controlled by accumulation of charged defects. *Nature materials*, [in press] 2016, 7 str., doi: 10.1038/nmat4799. [COBISS.SI-ID [29936679](#)]