

DOCTORAL STUDIES COURSE UNIT DESCRIPTION

Name of subject	Scientific Field	Center	Department
Technology of Semiconductors and their Structures (7,5 ECTS credits)	Materials Engineering T 008	Center for Physical Sciences and Technology	Physical Technologies Optoelectronics
Student's workload	Number of credits ECTS	Student's workload	Number of credits ECTS
Lectures		Consultations	
Individual study	7.5	Seminars	

Course annotation

Objectives and expected skills

Task of the study: To provide advanced knowledge on semiconductor materials, nanostructures, and device technologies, focusing on atomic-layer precision and band-gap engineering. Students will develop the capacity to design layered hybrid structures for next-generation devices, including high-efficiency radiation sources, quantum-dot detectors, multi-stimuli sensors, and neuromorphic hardware. A new emphasis is placed on energy-efficient fabrication and the integration of autonomous systems that convert complex physical signals into digitized data.

Skills to be improved: Students will refine their ability to critically evaluate and synthesize emerging trends in "More-than-Moore" scaling by analyzing diverse scientific sources. They will develop the professional competence required to apply predictive modeling for simulating semiconductor device performance prior to physical prototyping. Furthermore, the course fosters the capacity to understand and implement sustainable R&D practices, focusing on material lifecycles and the reduction of environmental impacts within modern cleanroom environments.

Content of the subject and main themes**1. Structure and Related Properties of Semiconductor Materials. Transfer Phenomena**

- Models for formation of semiconductor crystals and layers; growth methods.
- Structure, electronic and photonic properties, and charge transfer phenomena.
- Introduction to topological insulators and spin-polarized transport mechanisms.
- Physics and growth of Wide-Bandgap (WBG) and Ultra-WBG semiconductors: *GaN*, *SiC*, *Ga₂O₃*, and diamond.

2. Multilayer and Multicomponent Structures. Band Engineering

- Quantum structures: wells, superlattices, stripes, and dots.
- Intentional changes in the electronic structure ("band-gap-engineering"); *A₂B₆* and *A₃B₅* compounds and solid solutions.
- Tunnelling phenomena, band discontinuities; quantum transport (influence of magnetic field on 2D electrons, Shubnikov–de Haas experiments, quantum Hall effect).
- Moiré superlattices and "twistronics" in van der Waals heterostructures.

3. Optical Properties of Quantum Structures

- Excitons and shallow impurities in the quantum structures.
- Absorption, optical emission, interband transfer.
- Bloch oscillations; quantum limitations related to the Stark effect

4. Fabrication Technologies: Global Trends and Local Practice

- Mechanisms of thin film growth: epitaxy, stressed layers, nanocluster nucleation, and intergranular boundaries.
- Deposition methods: PVD, CVD (PECVD), MOCVD, MBE, and Atomic Layer Deposition (ALD).
- Atomic Precision: Area-selective deposition (ASD) and Atomic Layer Etching (ALE) for advanced scaling.
- Lithography (Practical): Mastery of UV writing and conventional mask alignment; mask design and photoresist chemistry.
- Lithography (Theoretical): Fundamentals of Extreme Ultraviolet (EUV), laser lithography and nanoimprint lithography for sub-10nm nodes.
- Advanced integration: Chiplet architectures, 3D integrated circuits (3D IC), and Through-Silicon Vias (TSV).
- Principles of CMOS technology, clean rooms, and contamination control.

5. Methods for Investigation of Materials and Nanostructures

- Structural characterization: X-ray structural analysis and high-resolution XRD.
- Chemical composition analysis: XPS, RBS, ESCA, SIMS, and Auger spectroscopy.
- Advanced microscopy: SNOM, SEM, TEM, and introduction to 4D-STEM and STEM-EELS.
- Optical and ultrafast characterization: Raman, FTIR, ellipsometry, and time-resolved photoluminescence.
- Synchrotron-based techniques: ARPES (angle-resolved photoemission spectroscopy) and XAS (X-ray absorption spectroscopy)

6. New Materials and Bottom-Up Technologies

- Nanostructured materials, hybrid structures, and bottom-up growth principles; self-arrangement.
- Two-dimensional (2D) materials of atomic thickness: Graphene, TMDs (MoS_2 , WS_2 , etc.), and MXenes.
- Perovskite semiconductors: Crystal structure engineering for optoelectronics and photovoltaics.
- Printing and writing methods for flexible electronics and wearable systems.

7. Semiconductor Based Structures for Signal Conversion and AI Hardware

- Detection of mechanical features (pressure, force, acceleration) and chemical sensing (gas sensors, ISFETs).

- Neuromorphic Computing: Memristive structures for artificial synapses and AI-on-chip hardware.
- Next-generation emitters: Laser diodes, Disk lasers, Quantum Cascade Lasers (QCLs), THz sources, and Micro-LED arrays.
- High-Performance Photovoltaics: Perovskite-silicon tandems and multi-junction solar cells.

List of literature

Core Semiconductor Textbooks

1. 1. Sze, S. M., & Ng, K. K. (2007). *Physics of Semiconductor Devices* (3rd ed.). Wiley-Interscience. ISBN 978-0-471-14323-9. <https://doi.org/10.1002/0470068329>
2. Dresselhaus, M., Dresselhaus, G., Cronin, S. B., & Souza Filho, A. G. (2018). *Solid State Properties: From Bulk to Nano*. Graduate Texts in Physics, Springer-Verlag GmbH Germany. ISBN 978-3-662-55920-8, ISBN 978-3-662-55922-2 (eBook). <https://doi.org/10.1007/978-3-662-55922-2>
3. Yu, P., & Cardona, M. (2010). *Fundamentals of Semiconductors: Physics and Materials Properties* (4th ed.). Springer. ISBN 978-3-642-00710-1. <https://doi.org/10.1007/978-3-642-00710-1>

Note: The 5th edition (2022) mentioned in the original list appears to be an error. The latest widely available edition is the 4th edition from 2010.

Manufacturing and Growth Techniques

4. Levinson, H. J. (2020). *Principles of Lithography* (4th ed.). SPIE Press, Bellingham, Washington. ISBN 978-1-5106-2760-4. <https://doi.org/10.1117/3.2525393>
 5. Cao, Z. (Ed.) (2011). *Thin Film Growth: Physics, Materials Science and Applications*. Woodhead Publishing Limited. ISBN 978-1-84569-736-5. <https://doi.org/10.1533/9780857094902>
- Note: Available online at Woodhead Publishing / Elsevier*
6. Lamberti, C., & Agostini, G. (Eds.) (2013). *Characterization of Semiconductor Heterostructures and Nanostructures* (2nd ed.). Elsevier. ISBN 978-0-444-59551-5 (hardback). <https://doi.org/10.1016/B978-0-444-59551-5.00001-7>

Emerging Materials and Quantum Phenomena

7. 7. Wood, C., & Jena, D. (Eds.) (2008). *Polarization Effects in Semiconductors: From Ab Initio Theory to Device Applications*. Springer. ISBN 978-0-387-36831-6 (hardcover), ISBN 978-0-387-68319-5 (eBook). <https://doi.org/10.1007/978-0-387-68319-5>
8. Solanki, M. B., & Jani, M. (2025). "Recent advancements in the development of 2D transition metal dichalcogenides (TMDs) and potential applications." *arXiv preprint arXiv:2509.12940*. <https://doi.org/10.48550/arXiv.2509.12940>
9. He, C., & Liu, X. (2023). "The rise of halide perovskite semiconductors." *Light: Science & Applications*, 12:15. <https://doi.org/10.1038/s41377-022-01010-4>
10. Goyal, R. K. (2024). "Exploring quantum materials & applications: A review." *arXiv preprint arXiv:2404.17594*. <https://doi.org/10.48550/arXiv.2404.17594>
Also published as: Goyal, R. K., Maharaj, S., Kumar, P., & Chandrasekhar, M. (2025). Journal of Materials Science: Materials in Engineering. <https://doi.org/10.1186/s40712-024-00202-7>
11. Liu, B., & Zhou, K. (2019). "Recent progress on graphene-analogous 2D nanomaterials: Properties, modeling and applications." *Progress in Materials Science*, 100, 99-169. <https://doi.org/10.1016/j.pmatsci.2018.09.004>

Advanced Characterization and Specialized Applications

12. Mikkelsen, A. (2024). "Characterization of semiconductors by synchrotron-based techniques" in *Comprehensive Semiconductor Science and Technology* (2nd ed.), Volume 2, pp. V2:540-V2:577. Elsevier. ISBN 978-0-323-96027-4 (print), ISBN 978-0-323-95819-6 (electronic). <https://doi.org/10.1016/B978-0-323-96027-4.00033-4>
13. de la Mata, M., & Molina, S. I. (2022). "STEM tools for semiconductor characterization: Beyond high-resolution imaging." *Nanomaterials*, 12(3), 337. <https://doi.org/10.3390/nano12030337>
14. Razeghi, M., et al. (2025). "High-power, high-wall-plug-efficiency quantum cascade lasers with high-brightness in continuous wave operation at 3–300 μ m." *Light: Science & Applications*, 14:252. PMC12297514. <https://doi.org/10.1038/s41377-025-01935-6>
15. Novoselov, K., et al. (2020–2024). "2D Materials: Properties and Device Applications" (Review Series). *Nature Reviews Materials*.
16. Huang, X., et al. (2022). "2D semiconductors for specific electronic applications." *npj 2D Materials and Applications*, 6:51. <https://doi.org/10.1038/s41699-022-00327-3>

Subject submission and evaluation

Teaching Approaches

The primary method for the subject study is independent, research-based learning. Consultations with responsible supervisors are available on an individual basis to discuss specific themes, practical fabrication challenges (e.g., UV-writing and mask alignment), or questions related to the course material.

Final Examination

The final assessment is a comprehensive test of knowledge based on a written report on a pre-defined topic. This report must synthesize the scientific and technological problems fundamental to the doctoral studies and the candidate's dissertation theme. The report should not exceed 30 pages (A4, Times New Roman 12pt, line spacing 1) and must disclose in detail how the research relates to at least 2–3 themes from the subject topics.

Assessment Method

The exam includes three parts with individual scoring. First, the report has to be submitted to the commission 2–3 weeks before the exam date. Second, an oral presentation based on slides has to be given during the exam session. The presentation must not exceed 30 minutes. The third part of the exam is based on the discussions after the oral presentation. The discussion is the process of the questions of the commission members and the answers of the student on the aspects of the topic of the report and the presentation.

The date of the exam is determined by agreeing between the members of the commission and the student after topic coordination. The scoring sum includes the report up to 3 points, the oral presentation up to 3 points, and answers to questions and discussions up to 4 points (total up to 10 points).

Consulting teachers	Scientific degree	Pedagogical name	Main scientific works published in a scientific field in last 5 year period
Jan Devenson (jan.devenson@ftmc.lt)	Dr.		1. Devenson, J., Stasys, K., Norkus, R., Stanionyte, S., & Krotkus, A. (2023). Intervalley energy separation in the

			conduction band of InAs_{1-x}Bi_x determined by terahertz emission spectroscopy. Japanese Journal of Applied Physics, 62(4), 5. DOI: 10.35848/1347-4065/acc777 2. Stašys, K., Geižutis, A., & Devenson, J. (2024). Enhanced thermal emission from metal-free, fully epitaxial structures with epsilon-near-zero InAs layers. Journal of Semiconductors, 45(2), 022101. DOI: 10.1088/1674-4926/45/2/022101 3. Paulauskas, T., Devenson, J., Stanionyte, S., Skapas, M., Karpus, V., Cechavicius, B., ... Pacebutas, V. (2022). Epitaxial growth of GaAsBi on thin step-graded InGaAs buffer layers. Semiconductor Science and Technology, 37(6), 8. DOI: 10.1088/1361-6641/ac61ff 4. Devenson, J., Norkus, R., Juskenas, R., & Krotkus, A. (2021). Terahertz emission from ultrathin bismuth layers. Optics Letters, 46(15), 3681-3684. DOI: 10.1364/ol.425271 5. Paulauskas, T., Pacebutas, V., Butkute, R., Cechavicius, B., Naujokaitis, A., Kamarauskas, M., ... Devenson, J., ... Krotkus, A. (2020). Atomic-Resolution EDX, HAADF, and EELS Study of GaAs_{1-x}Bi_x Alloys. Nanoscale Research Letters, 15(1), 12. DOI: 10.1186/s11671-020-03349-2
Renata Butkutė (renata.butkute@ftmc.lt)	Dr.	Doc.	1. A.Vaitkevičius, A. Špokas, A. Zelioli, U. Cibulskaitė, A. Bičiūnas, E. Dudutienė, B. Čechavičius, M. Skapas, A.Čerškus, M. Talaikis, P. Baranowski, P. Wojnar, R. Butkutė, Segregation-driven formation of bismuth quantum dots in parabolic GaAsBi/AlGaAs quantum structures, Surfaces and Interfaces, Volume 68, 106586 (2025); https://doi.org/10.1016/j.surfin.2025.106586 2. Špokas A. Zelioli, A. Bičiūnas, B. Čechavičius, J. Glemža, S. Pralgauskaitė, M. Kamarauskas, V. Bukauskas, J. Spigulis, Y-J. Chiu, J. Matukas, R. Butkutė, Optimising (Al,Ga) (As,Bi) Quantum Well Laser Structures for Reflectance Mode Pulse Oximetry, Micromachines, 16, 506 1-10 (2025); https://doi.org/10.3390/mi16050506 3. Evelina Dudutienė, Algirdas Jasinskas, Sandra Stanionytė, Martynas Skapas, Augustas Vaitkevičius, Bronislovas echavičius, Renata Butkutė, Impact of

			elevated GaAs barrier growth temperature on the homogeneity and photoluminescence of GaAsBi multiple quantum wells, <i>Materials Science in Semiconductor Processing</i>, Vol. 199, 109828 (2025); https://doi.org/10.1016/j.mssp.2025.109828 4. Andrea Zelioli, Aivaras Špokas, Bronislovas Čechavičius, Martynas Talaikis, Sandra Stanionytė, Virginijus Bukauskas, Augustas Vaitkevičius, Aurimas Čerškus, Piotr Wojnar, Vitaly Deibuk, Evelina Dudutienė & Renata Butkutė, Comprehensive investigation of emission homogeneity of InGaAs multiple quantum wells using spatially resolved spectroscopy, <i>Scientific Reports</i>, (2025) 15:32885; https://doi.org/10.1038/s41598-025-17326-1 5. J. Glemža, A. Špokas A. Zelioli, M. Kamarauskas, A. Bičiūnas, B. Čechavičius, J. Spigulis, Y-J. Chiu, S. Pralgauskaitė, J. Matukas, R. Butkutė, Quality evaluation of NIR laser diodes for medical application using low-frequency noise characterization, <i>Infrared Physics and Technology</i>, 147, 105794 (2025); https://doi.org/10.1016/j.infrared.2025.105794 6. M. Skapas, E. Luna, S. Stanionytė, K. Graser, R. Butkutė, In Situ TEM Study of Size-Controlled Bi Quantum Dots in an Annealed GaAsBi/AlAs Multiple Quantum Well Structure, <i>ACS Omega</i> 10(10), 10432–10437 (2025); DOI:10.1021/acsomega.4c10631 7. A. Štaupienė, A. Zelioli, A. Špokas, A. Vaitkevičius B. Čechavičius, S. Stanionytė, S. Raišys, R. Butkutė, E. Dudutienė. Internal quantum efficiency of GaAsBi MQW structure for the active region of VECSELs. <i>Appl. Phys. Lett.</i> 125, 221102 (2024); 10.1063/5.0234853 8. Armalytė, S.; Glemža, J.; Jonkus, V.; Pralgauskaitė, S.; Matukas, J.; Pūkienė, S.; Zelioli, A.; Dudutienė, E.; Naujokaitis, A.; Bičiūnas, A.; Čechavičius, B.; Butkutė, R. Low-Frequency Noise Characteristics of (Al, Ga)As and Ga(As, Bi) Quantum Well Structures for NIR Laser Diodes. <i>Sensors</i> 2023, 23, 2282. https://doi.org/10.3390/s23042282
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			9. Ignas Grigelionis, Vladislovas Čižas, Mindaugas Karaliūnas, Vytautas Jakštas, Kęstutis Ikamas, Andrzej Urbanowicz, Marius Treideris, Andrius Bičiūnas, Domas Jokubauskis, Renata Butkutė, Linas Minkevičius, Narrowband Thermal Terahertz Emission from Homoepitaxial GaAs Structures Coupled with Ti/Au Metasurface, Sensors, Volume 23, Issue 10, 4600 (2023). 10. Karpus Vytautas; Čechavičius Bronislovas; Tumėnas Saulius; Stanionytė Sandra; Butkutė Renata; Skapas Martynas; Paulauskas Tadas, Optical anisotropy of CuPt-ordered GaAsBi alloys, J. Phys. D: Appl. Phys. 54 (2021) 504001 (8pp) https://doi.org/10.1088/1361-6463/ac244a 11. Mindaugas Karaliūnas, Evelina Dudutienė, Aurimas Čerškus, Justas Pagalys, Simona Pūkienė, Andres Udal, Renata Butkutė, Gintaras Valušis, High precision parabolic quantum wells grown using pulsed analog alloy grading technique: Photoluminescence probing and fractional-dimensional space approach, Journal of Luminescence, Vol. 239, p. 118321 (9 ps) (2021), https://doi.org/10.1016/j.jlumin.2021.118321
Certified by the Doctoral Committee of Material Engineering (T 008) on 24/02/2026, protocol No. 5.2.2 E-15600-KT-725			
Committee Chairman dr. Arūnas Kadys			