Synthesis and Spectroscopic Characterization of 2D Materials, and its applications

1. Introduction

The rapid development of nanotechnology relies, among other things, on high-tech synthesis and integration of two-dimensional materials (2DMs), such as transition metal dichalcogenides, graphene, and others. One of the key challenges is the controlled production of high-quality monolayers and van der Waals heterostructures, as well as the development of non-destructive methods for their structural characterization. Simultaneously, Raman spectroscopy of biological molecules (e.g., peptides) often faces the problem of thermal sample degradation under laser exposure, which limits the reliability of structural analysis. At JINR, active research is being conducted in condensed matter physics and nanomaterials, including scalable synthesis methods for low-dimensional materials and advanced optical characterization.

This project focuses on plasma-enhanced chemical vapor deposition (PECVD) synthesis of molybdenum disulfide (MoS_2) and graphene, as well as spectroscopic quality control. One of the promising practical applications is the use of monolayer graphene as a thermally conductive protective coating to preserve the structural integrity of ultra-low concentration peptides during Surface-Enhanced Raman Scattering (SERS)/Raman measurements.

2. Main Part:

During the 3-week internship, participants will:

1. Gain practical skills in PECVD synthesis of monolayer graphene on copper foil and MoS_2 on Si/SiO_2 substrates.
2. Master wet transfer methods for graphene and formation of MoS_2/graphene heterostructures.
3. Study the principles of confocal Raman spectroscopy adapted for 2DMs (identification of G, 2D, D bands in graphene; E_2g, A_1g modes in MoS_2; signs of interlayer interaction).
4. Learn strategies to reduce photothermal damage of bio-samples in Raman spectroscopy.
5. Conduct spectral analysis (peak fitting, evaluation of intensities/shifts/full width at half maximum, determination of layer number).
6. Prepare and present results in the form of a scientific report.

3. Description of Project Work:

3.1. Setup (photo and schematic):

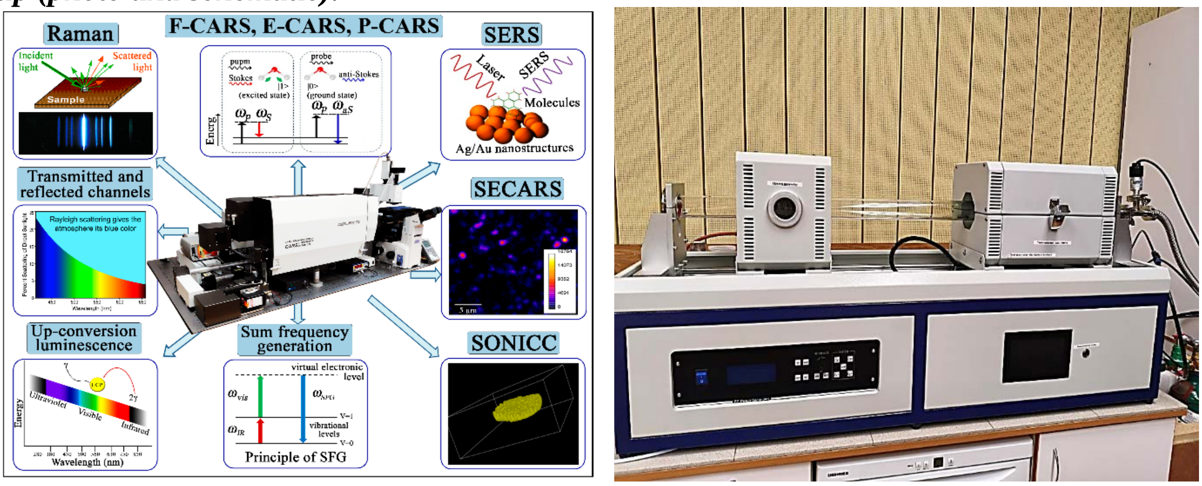

Figure 1. Multifunctional 3D Scanning Laser MicroSpectrometer Confotec® CARS (left) and Plasma Enhanced Chemical Vapor Deposition (PECVD) System (right).

3.2. Measurement Procedure:

1. **Synthesis and characterization**: Synthesis of MoS_2 on Si/SiO_2 substrate and monolayer graphene on copper foil with optimized PECVD parameters.
2. **Primary Raman mapping** to evaluate the number of layers, crystallinity degree, and defect density.
3. **Transfer and heterostructure assembly**: Wet transfer of monolayer graphene onto MoS_2 film. Raman characterization of the MoS_2/graphene stack to confirm van der Waals coupling and interface quality.
4. **Bio-sample preparation and thermal protection**: Deposition of target peptide solution onto SERS-active substrate followed by drying. Second graphene transfer to completely cover the peptide layer.

5. **Comparative Raman analysis**: Recording peptide spectra on SERS substrate with and without graphene at the same laser power. Stepwise power variation to determine the damage threshold and evaluate spectral preservation.
6. **Data processing**: Baseline correction, peak deconvolution, quantitative comparison of band positions/intensities. Correlation of spectral stability with thermal conductivity and protective properties of graphene.

3.3. Form of Results Presentation:

1. A brief scientific report (2–3 pages) with methodology, processed spectra, comparative analysis, and conclusions on graphene protection effectiveness.
2. A short oral or poster presentation on the results of synthesis, low-dimensional material characterization, and bio-protection.

4. Requirements for Student Preparation:

1. Basic courses in solid-state physics, physical chemistry, or materials science.
2. Familiarity with fundamentals of optical spectroscopy is desirable.
3. Experience with data analysis software (Origin Pro or analogs) is highly desirable.
4. Ability to follow strict safety regulations, especially during chemical transfer processes and laser operation.
5. Motivation for research work and ability to work independently under supervision.

5. Recommended Literature:

1. Li, X., et al. (2010). Large-area synthesis of high-quality and uniform graphene films on copper foils. Science, 324(5932), 1312–1314. https://doi.org/10.1126/science.1171245
2. Ferrari, A. C., & Basko, D. M. (2013). Raman spectroscopy as a versatile tool for studying the properties of graphene. Nature Nanotechnology, 8(4), 235–246. https://www.nature.com/articles/nnano.2013.46
3. Lee, C., Yan, H., Brus, L. E., Heinz, T. F., Hone, J., & Ryu, S. (2010). Anomalous Lattice Vibrations of Single- and Few-Layer MoS2. ACS Nano, 4(5), 2695–2700. https://doi.org/10.1021/nn1003937
4. Zhao, Y.; Xie, Y.; Bao, Z.; Tsang, Y. H.; Xie, L.; Chai, Y. Enhanced SERS Stability of R6G Molecules with Monolayer Graphene. J. Phys. Chem. C 2014, 118 (22), 11827– 11832. https://pubs.acs.org/doi/10.1021/jp503487a
5. Geim, A. K., & Grigorieva, I. V. (2013). Van der Waals heterostructures. Nature, 499(7459), 419–425. https://doi.org/10.1038/nature12385

6. Number of Participants:

2 students. Participants will jointly perform synthesis and transfer, then conduct individual Raman characterization and data analysis, or work as a single research team.

7. Project Supervisor from JINR:

Full Name: Mamatkulov Kahramon
Position, Academic Degree: Head of the Group: "Nonlinear Microspectroscopy"
Laboratory, Department: Laboratory of Neutron Physics, Sector of Raman Spectroscopy
Scientific Interests: PECVD synthesis of 2DMs, Raman spectroscopy in life sciences and low-dimensional systems, van der Waals heterostructures, protective coatings for biospectroscopy.
Scientific Results:

1. Encapsulation of lysozyme within graphene sandwich reduces its thermal denaturation during SERS-analysis, International Journal of Biological Macromolecules, Volume 330, Part 1, 2025, 148048, ISSN 0141-8130, https://doi.org/10.1016/j.ijbiomac.2025.148048.
2. Conformational analysis of lipid membrane mimetics modified with Aβ42 peptide by Raman spectroscopy and computer simulations, Journal of Biomolecular Structure and Dynamics 1–14 (2024). https://doi.org/10.1080/07391102.2024.2330706.
3. Surface Enhanced Raman Spectroscopy of Lactoferrin Adsorbed on Silvered Porous Silicon Covered with Graphene, Biosensors 2019, 9(1), 34; https://doi.org/10.3390/bios9010034.