Enhancing Optical and Mechanical Properties of Structured Surfaces through Multifunctional Coatings and Advanced Simulations

The fabrication of structured optical surfaces inspired by biomimetic principles has led to remarkable improvements in antireflective properties, hydrophobicity, and mechanical resistance. However, their long-term durability in harsh environments remains a key challenge. This PhD project aims to optimize the mechanical robustness and optical performance of structured surfaces through a multi-faceted approach: combining advanced coating strategies, computational modeling (FEM, optical simulations), and large-scale fabrication techniques. The research will focus on nano-engineered coatings (metal oxides, spinel phases, elastic materials), heat treatments, and novel deposition methods (sol-gel, ALD, spin-coating) to enhance surface resilience without compromising optical transparency. Additionally, mechanical simulations (FEM) will be used to predict failure modes and guide coating design, while new materials such as diamond-like carbon and perovskites will be explored. The project will also address scalability, aiming for double-sided structuring and industry-compatible large-area deposition techniques to facilitate real-world applications in smart optical coatings, energy-efficient windows, and aerospace materials.

Objectives:

Develop protective coatings for structured optical surfaces using materials such as ZnO, Al_2O_3, $ZnAl_2O_4$, DLC, and flexible polymers (PMMA, PDMS).
Investigate heat treatment strategies to induce phase transformations (e.g., spinel phase formation) for mechanical reinforcement.
Implement FEM-based mechanical modeling to simulate scratch resistance, compressive stress, and elastic recovery of coated structures.
Refine optical simulations using advanced modeling to better account for defects and scattering.
Optimize deposition techniques (sol-gel, ALD, spin-coating) for large-scale structuring and cost-effective coatings.
Evaluate real-world mechanical performance through standardized tests (abrasion, adhesion, erosion) and correlate results with nanoscratch tests.
Explore alternative structured substrates such as glass, sapphire, and ZnS for application in smart windows and optical lenses.

Methodology:

This project will employ a combination of experimental synthesis, computational simulations, and standardized testing:

- Surface Fabrication & Coating Deposition:
Structuring of Si, Ge, or alternative materials via photolithography and etching.
Application of conformal coatings (ZnO, Al_2O_3, DLC, PMMA) using ALD, sol-gel, and spin-coating.
Heat treatment for phase transformation (ZnO/Al_2O_3 to $ZnAl_2O_4$ spinel).
- Characterization of Optical & Mechanical Properties:
Spectrophotometry & ellipsometry for reflectivity and refractive index analysis.
Nanoindentation & nanoscratch tests to assess mechanical durability.
SEM, TEM, AFM, and ToF-SIMS for structural and surface chemistry analysis.
Computational Modeling & Simulation:
Finite Element Method (FEM) to simulate mechanical deformation under stress.
Supercell optical modeling to analyze scattering and light-matter interaction.
Application-Oriented Testing & Scalability:
Develop double-sided structuring methods to enhance surface performance.
Scale up coatings for large-area deposition and assess industry compatibility.

Expected Outcomes & Innovation:

Enhanced mechanical durability of structured optical surfaces through novel coating strategies.
New insights into mechanical stress responses via FEM-based simulations.
Optimized optical performance through improved supercell modeling.
Scalable and cost-effective fabrication techniques for industrial adoption.
Potential applications in smart windows, aerospace coatings, and next-generation optical materials.