Executive Summary of Activities Conducted in 2025

In 2025, the HafGraphX project successfully completed the first development phase of an innovative hybrid X-ray imaging detector based on hafnium oxide (HfO_2) thin films and graphene integrated into G-FET structures. This phase focused on establishing the material, technological, and experimental framework required for developing the demonstrator in the next stage.

1. HfO_2 Thin Films Synthesized via ALD

Pure and doped (Zr, Al, Y) HfO_2 thin films with thicknesses of 7 nm and 100 nm were synthesized using atomic layer deposition (ALD). The process provided atomic-level thickness control, excellent uniformity, and homogeneous dopant distribution. GIXRD, XRR, AFM, and SEM/EDS analyses confirmed the structural and morphological quality of the films. Among the studied materials, pure HfO_2 and HfYO exhibited the highest electrical stability and strongest potential for X-ray detection.

2. X-ray Response of HfO_2-Based Films

Current–voltage measurements, performed both in the absence of irradiation and under Cu Kα (~8 keV) exposure, revealed:
• Undoped HfO_2: dose-dependent current increases of +50–60%;
• HfYO: the strongest radiation response, attributed to the high density of oxygen vacancies and F-centers;
• HfAlO and HfZrO: low or impaired sensitivity due to ferroelectric behavior.
These findings identify HfO_2 and HfYO as the optimal active dielectrics for subsequent development stages.

3. Design, Fabrication, and Characterization of G-FET Devices

G-FET structures with channel lengths of 50 and 60 µm were fabricated using photolithography and Cr/Au metallization. CVD graphene was transferred onto these structures via electrochemical delamination, a method that minimizes contamination and preserves the integrity of the 2D layer.
Raman spectroscopy and AFM analyses confirmed the high quality of both single-layer (SLG) and bilayer (BLG) graphene.

4. X-ray Sensitivity of G-FET Structures

The G-FET devices displayed significant increases in current and conductance under X-ray exposure:
• sensitivities ranging from +40% to over +120%;
• reproducible positive photoconductivity across all configurations.
While SLG devices exhibit higher baseline currents, BLG devices demonstrate:
• more than double the relative sensitivity;
• conductance increases exceeding +120–130%;
• superior electrical stability and an enhanced signal-to-noise ratio.
Consequently, BLG graphene was selected as the optimal channel material for the detector prototype.

5. Optimal Materials and Architecture for Stage 2

The integrated results led to the identification of the optimal material configuration for the test structures:
• Undoped HfO_2 – stable, reproducible dielectric;
• HfYO – material with maximum X-ray sensitivity;
• BLG graphene – channel material with a robust and highly responsive electrical behavior.
This hybrid architecture maximizes detector sensitivity and provides a solid technological foundation for developing the demonstrator in the next stage.

Conclusions

Phase 1 (2025) was completed with full achievement of all planned objectives:
• synthesis and comprehensive characterization of pure and doped HfO_2 thin films;
• fabrication of G-FET structures compatible with graphene integration;
• implementation of electrochemical transfer of SLG and BLG graphene;
• demonstration of X-ray sensitivity for both HfO_2/HfYO dielectrics and G-FET devices;
• publication of an Open Access scientific article and dissemination of results at an international conference.
These results validate the technological feasibility of the hybrid detector concept based on HfO_2 and graphene and provide the scientific and experimental basis necessary for developing the functional X-ray detector demonstrator in the next phase.