Enabling Ferroelectric Characterization through BE-PFM and Python API

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Abstract

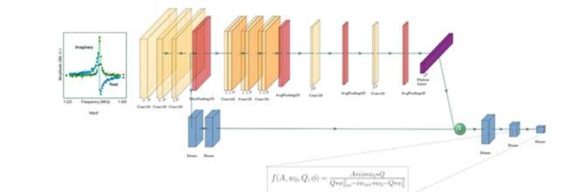
The ever-expanding use of multimodal scanning probe microscopy (SPM) and spectroscopy has led to a surge in data volume and complexity. To tackle this, machine learning techniques have emerged for scientific interpretation. However, the time-consuming nature of these methods limits real-time analysis, hindering techniques like band-excitation piezoresponse force spectroscopy (BE PFM). Our approach is to minimize latency by establishing a direct channel between an analog-to-digital converter and an FPGA via the NI PXI platform. This FPGA-based pipeline, developed using LabVIEW and hls4ml, achieves microsecond-level latencies, enabling real-time predictions of simple harmonic oscillator fits for BE PFM. Overlapping data acquisition with computation ensures continuous processing. This work sets the groundwork for deploying on-sensor neural networks using specialty hardware for real-time control of materials imaging systems.

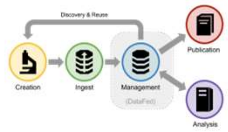
This project aims to democratize Band-Excitation Piezoresponse Force Microscopy (BE-PFM) for ferroelectric analysis. Traditionally confined to facilities like Oak Ridge National Laboratory, we strive to make BE-PFM accessible in labs. Our focus involves signal processing algorithms for precise BE-waveform application to AFM tips, a measurement setup with a National Instruments oscilloscope, and a versatile switching spectroscopy setup with a Python interface. The goal is to enable switching spectroscopy on diverse ferroelectric materials, enhancing our understanding of their behavior and properties.

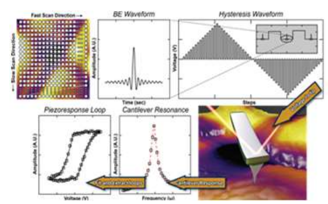
To facilitate this, we've developed a Python API that streamlines control, data acquisition, and analysis by connecting Python and the experimental setup. Additionally, we've created an Igor-based front-end panel for the Oxford Instruments Cypher AFM, allowing direct connection to DataFed for efficient data storage. Integration with tools like Pycroscopy further enriches data analysis, making this project a significant step towards advancing material studies and scientific discovery.

Methods

- Piezoresponse Force Microscopy (PFM): A set of imaging techniques where a sharp cantilever tip "scans" the surface of a sample; an AC voltage is applied to measure the piezoelectric properties of a material.
- Band Excitation PFM: A PFM technique where an excitation spanning a band of frequencies is applied, enabling study of the material's frequency dependence, dielectric and piezoelectric properties, and response to real world conditions (temperature, radiation, EM fields, mechanical stress, etc.)
- Python API: To optimize control, data acquisition, and analysis, we designed a Python API. This interface simplifies hardware interaction and empowers researchers to efficiently configure experiments, gather data, and conduct analyses.
- Igor Front Panel: We developed an Igor-based front panel connected to a python back end for direct control of the data and file storage of Oxford Instruments Cypher AFM. This graphical user interface streamlines data and file uploading to DataFed which allows for efficient storage of metadata. This cohesive integration enhances accessibility and user experience, enabling seamless experiment data management.

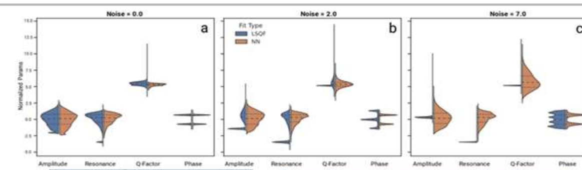


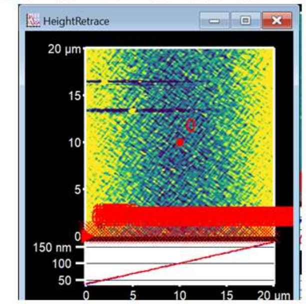




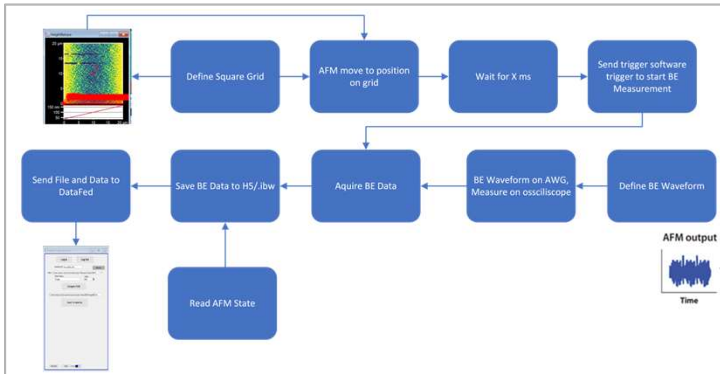
Results

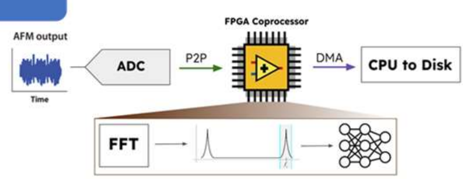
- SHO Fitter model and HLS model achieve ~0.053 MSE, outperforming least-squares fitting
  - Trained quantization aware; parameters quantized to 16 bits with marginal performance loss
- LabVIEW data acquisition and model firmware completed
- Achieved 36us first-in last-out FPGA model latency with over 60% of fabric resources still available
- A Python API allowing streamlined control and implementation of BE
- An Igor front end based and Python back end-based panel that allows for direct connection to DataFed for efficient data storage, from the Oxford Instruments Cypher AFM





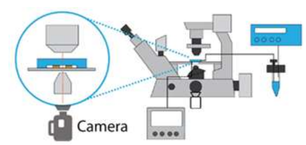
Pipeline

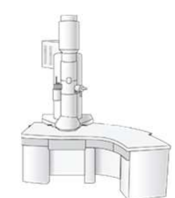




Future Work

- API for automated analysis
- Python package for neural network fitting with hard physics constraints
- Deploy on RFSoC





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