DOI 10.5162/SMSI2023/D5.1

Compressed nano-FTIR Hyperspectral Imaging for Characterizing Defects in Semiconductors

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Summary:
In the field of power electronics, the ongoing development of wide-bandgap compound semiconductors is limited by material defects, which compromise device performance and reliability. New metrological tools are required with high sensitivity to local material properties, such as noninvasive nano-FTIR hyperspectral imaging to map properties such as: crystal structure, carrier density, or strain on the nanoscale. However, full spatio-spectral imaging is constrained by long measurement times. Here we discuss a compression method that allows us to reduce the measurement time by up to 90%.

Keywords: power electronics, semiconductor defects, nano-FTIR, compressed spectroscopy, low-rank matrix reconstruction.

Introduction

In infrared (IR) hyperspectral imaging (HSI) a spectrum is recorded at each pixel of a 2D specimen. It is a powerful tool for contactless material characterization utilized in analytical chemistry [1], microelectronics [2] and for novel functional materials [3]. In this work, we consider HSI with nanoscale spatial resolution using nano-FTIR [4]. However, HSI results in large data sets which are acquired in long, often unfeasible acquisition times. We therefore discuss a compression strategy to be employed at the measurement stage to image defects in the wide-bandgap semiconductor 4H-SiC which is particularly relevant for applications in the field of power electronics. We show that the amount of measured data can be reduced by up to 90% while keeping the information relevant for defect characterization in the reconstructed data.

Method

Nano-FTIR is a scanning-based technique which combines Fourier transform infrared spectroscopy (FTIR) and scattering-type scanning near-field optical microscopy. In nano-FTIR spectroscopy is realized by passing broadband IR radiation through an asymmetric Michelson interferometer containing a metallized tip of an atomic force microscope (AFM) in close proximity to the sample in one of the arms while the length of the reference arm is defined by a movable mirror. Here we employ a NeaSNOM instrument from Attocube GmbH operated using wideband synchrotron radiation [9]. For single-frequency imaging a quantum cascade laser is employed. The compression strategy was based on a low-rank matrix reconstruction method that was previously developed in Ref. [5] for FTIR measurements. It couples the spatial domain and the interferometer axis by reconstructing the most significant factorized basis elements. An additional incorporation of spatial smoothness using a Tikhonov regularization enhances our treatment and an L-curve criterion adapts the additional parameter.

Nearfield imaging of a triangular SiC defect

We demonstrate our method by imaging a triangular defect, which typically exhibits a polytype inclusion within a homoepitaxial layer of 4H-SiC layer. The inset of Fig. 1 shows an IR nearfield phase image of a defect-section recorded at 940 cm^{-1}. While there is clear contrast the interpretation is ambiguous since it can be caused by several factors.

A simulation of the nearfield phase for varying doping and polytype is shown in Fig. 1, both of which may vary spatially around defects. Therefore, it is not sufficient to image at a single frequency but to record the complete spectrum at each pixel.

Compressed nano-FTIR imaging

The same defect has also been imaged using the nano-FTIR method. Interferograms are recorded by continuous movement of the reference mirror. They contain information about both, the phase and amplitude of the radiation scattered from the AFM tip. This means that the interferograms are measured directly while the spectrum is obtained by Fourier transformation. The phase spectrum can then be compared to the diagrams in Fig. 1.

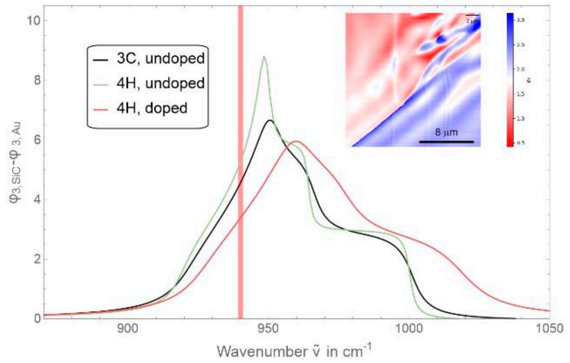

Fig. 1. Simulated phase spectra for 3C and 4H SiC polytypes and different doping; inset: nearfield phase image measured at 940 cm^{-1}.

The topography of the imaged defect is shown in the atomic force microscopy image in the inset of Fig. 2. The measurement time of each spectrum was 14 s. For demonstration purposes the spatial resolution was limited to 13x13 pixels within the red square marked in the topography image resulting in a total measurement time of 40 minutes.

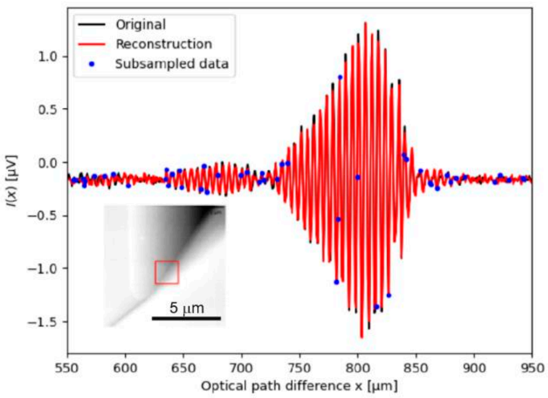

Fig. 2. Measured and reconstructed interferograms and topography of the defect-section.

Fig. 2 shows an example-interferogram from which the nearfield phase spectrum can be calculated. To illustrate that the amount of data can be reduced while keeping the relevant spectral information we randomly selected only 10% of the measurement points (blue dots). When applying the reconstruction algorithm of Ref. [5] the remaining 90% of the datapoints have been mathematically reconstructed. The reconstructed curve is plotted in red over the original curve in black. Note that the reconstruction algorithm relies on the ensemble of subsampled interferograms.

Conclusion and Outlook

We have shown that the amount of data in nano-FTIR hyperspectral imaging can be significantly reduced by considering the example of a triangular polytype defect in 4H-SiC. Depending on spectral properties such as sparsity and further prior knowledge about the sample alternative algorithms [6] or extensions [7] may be employed. The random selection of data may lead to idle times during the measurement when transferring between different datapoints. This issue has been discussed in Ref [8] where specific continuous measurement routes have been suggested which do not significantly affect the reconstruction quality using the low-rank algorithm. This will facilitate hardware implementations in commercially available instruments, such as the one employed in this work.

Acknowledgement

The work was partially funded within the project 20IND09 PowerElec from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. We acknowledge financial support by Deutsche Forschungsgemeinschaft (Grants EL 492/1-1, RU 420/13-1).

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