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Computational inspection of VCSEL oxidation exploiting a spectrally-shaped illuminator

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Abstract: We introduce a co-design approach for VCSEL inspection using sinusoidal illumination, well-suited for multi-layer inspection tasks. This methodology shows potential for varied monitoring and inspection tasks, aiming to improve precision in optoelectronic manufacturing. © 2024 The Author(s)

1. Introduction

In the semiconductor industry, the development of high-yield, low-cost optoelectronic and microelectronic devices hinges on precise process control, making real-time monitoring and post-process inspection critical. Specifically, for Vertical-Cavity Surface-Emitting Lasers (VCSELs)—key components in data communication—the monitoring and inspection of the lateral oxidation step is pivotal since the latter defines the oxide aperture that controls its electrical and optical characteristics. Advances in inspection techniques, particularly those leveraging oxidation-induced changes in reflectivity, have led to the development of sophisticated systems [1–4]. Our latest system utilizes spectrally-shaped illumination with a CMOS camera, markedly improved the detection of oxidized versus unoxidized regions by matching the illumination spectrum to the reflectivity difference between these areas [4].

Here, we introduce a new end-to-end differentiable framework that streamlines the design process by simultaneously training a spectrally-shaped illumination generator and an image processing algorithm. This method transitions from traditional image contrast enhancement to a holistic co-design approach, facilitating not only simpler illumination setups but also setting the basis for addressing more complex tasks, like anomaly detection.

2. Generation of the oxide-confined VCSEL image dataset

Our streamlined approach begins with the generation of a dataset for optimizing our VCSEL monitoring computational framework. Our simulations concentrate on conventional oxide-confined VCSELs that are based on AlGaAs semiconductors, operate at a wavelength of 850 or 940 nm and are partly laterally oxidized from etched mesas of circular, square or hexagonal shape. A set of 12000 hyperspectral images are created by defining the spatial structures using open-source Blender software and the local spectral response using thin-film (Scattering Matrix method-based) reflectometry calculations. The etched mesas of varied size are fully contained but randomly positioned within the image and the oxidized areas of various lateral extent are defined by employing stage-by-stage binary anisotropic convolution kernels whose size is set by the aluminum concentration-controlled oxidation rate [5]. Some defects have also been added at this stage to enhance realism. The spectral response is evaluated using an weighted-average unpolarized reflectivity calculation over the acceptance angle of the microscopy-based imaging system.

3. Co-design of the spectrally-shaped illumination and detection algorithm

Our end-to-end differentiable framework significantly advances the method for determining the optimal illumination spectrum tailored to specific inspection tasks. The primary focus is the precise segmentation of the oxidized regions in images captured by the monitoring system, highlighting areas critical for assessing VCSEL quality.

Initial analysis of the reflectivity spectra, obtained from epitaxial data or early-stage hyperspectral cube analysis, informed the hereafter chosen illumination strategy [4]. We leverage a 1D convolutional neural network equipped with residual blocks to extract information from these reflectivity spectra, guiding the generation of a sinusoidal illumination pattern characterized by specific frequency p_0 and phase parameter p_1 , as illustrated in figure 1 (a). In practice, this spectral shape would be achievable in a compact way by a white lamp filtered by a variable-delay Mach-Zehnder interferometer.

To simulate camera acquisitions accurately, our framework incorporates models of the optical point-spread function, Newton rings interference, and detector noise (including shot and read-out noise) as presented on figure 1 (b). This comprehensive simulation environment, detailed in our repository [6], supports the training of

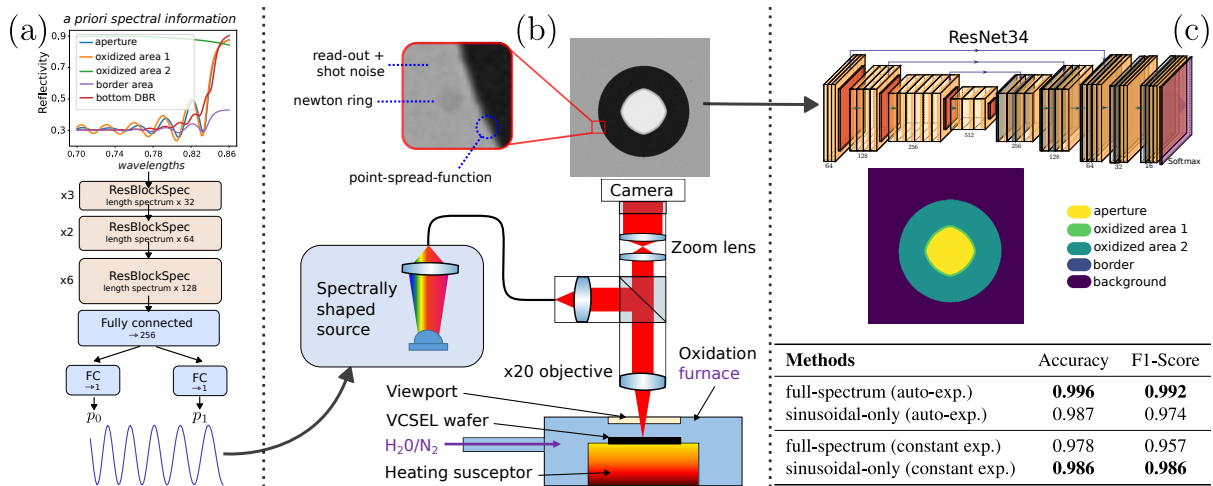


Fig. 1. End-to-end computational framework for VCSEL lateral oxidation monitoring: (a) sinusoidal sipectrum illumination generator; (b) illumination and monitoring setup; (c) segmentation neural network and associated results.

a ResNet34 architecture for the segmentation task. Renowned for its effectiveness in image segmentation, the ResNet34 architecture is trained to distinguish oxidized regions with high precision. The training process utilizes the differentiable framework to optimize both the neural network and the illumination spectrum generator, ensuring the methodology effectiveness. Key to this process is a balanced approach to the loss function design, emphasizing the importance of accurately segmenting the unoxidized regions. Initially, the illumination pattern is constrained on the basis of the reflectivity contrast spectral analysis.

We compare segmentation outcomes under two illumination strategies: full spectrum control and sinusoidal-only control, assessed across two detection scenarios—with and without auto-exposure. The data presented in Figure 1 (c) illustrates that employing auto-exposure, which adjusts exposure time to mitigate readout noise, the arbitrary spectrum control leads to superior results, as anticipated. Conversely, when exposure times are constant, the sinusoidal strategy, refined via joint training, offers improved results by allowing more light through the monitoring setup and thus providing images with less noise. Notably, the sinusoidal-only control consistently delivers satisfactory outcomes, making it a promising candidate for experimental validation.

4. Conclusion

In this contribution, we presented an advanced computational framework to advance oxide-confined VCSEL inspection and monitoring. We introduced a simplified system informed by experimental insights exhibiting a sinusoidal-spectrum illumination. This co-design approach not only refines the inspection process but also exhibits efficiency across different exposure settings, indicating its viability for experimental adoption. Although we focused our attention to segmentation results, our task-driven methodology is adaptable to a range of inspection tasks, thereby highlighting the flexibility and potential of combining software algorithms with hardware configurations to enhance process monitoring tasks in optoelectronic device manufacturing.

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