20 – 23 July 2020

27th INTERNATIONAL SYMPOSIUM ON THE PHYISICAL AND FAILURE ANALYSIS OF INTEGRATED CIRCUITS

20 – 23 July 2020

SINGAPORE

Conference eProceedings

Organized by:

IEEE RS/EPS/EDS Singapore Chapter

Technically co-sponsored by:

Electron Devices Society

Reliability Society

Honoured Sponsors:

Digit Concept

kleindiek nanotechnik

Divergent Technologies

SEMICAPS Excellence In Innovation

ThermoFisher SCIENTIFIC

Application of Circular Differential Interference Contrast Imaging in Semiconductor Failure Analysis Workflow

Kelvin Loh[1], Vignesh Viswanathan[1]
[1]Research Microscopy Solutions, Carl Zeiss Pte Ltd, 50 Kaki Bukit Place, #05-01, Singapore 415926
Phone : (+65)97274077, Email : kelvin.loh@zeiss.com

***Abstract*— The circular differential interference contrast (C-DIC) imaging module provides a novel contrast mechanism to end-point and precisely identify different layers in the semiconductor die BEOL. This provides a unique value add in the semiconductor FA workflow to streamline delayering and optical inspection step for improved efficiency and higher throughput especially in the sub-10 nm nodes.**

Keywords—C-DIC, delayering, BEOL, optical inspection.

I. Introduction

Microscopy in semiconductor manufacturing can be categorized into a) Inline wafer inspection, b) offline inspection for defect review and failure analysis and c) CD measurement and overlay metrology [1]. Optical microscopy techniques variants by scaling the wavelength to the VUV [2], employing through focus optical microscopy [3-4], interferometry [5-6], phase contrast and additional image processing techniques [7], have been employed for in-line and offline defect inspection and metrology. In failure analysis workflows, traditional optical microscopy employing various contrast mechanisms such as bright-field, dark-field, polarization and differential interference contrast (DIC) are common to identify various defects such as scratches, organic and inorganic contaminants in packages and die.

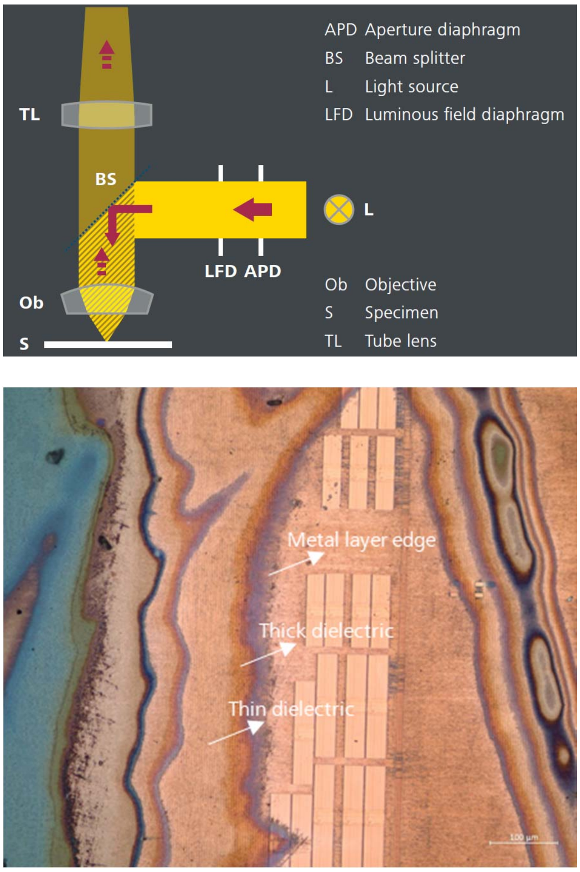
For workflows that employ mechanical polishing or parallel lapping during the physical failure analysis of the die, frequent and fast inspection of die for end-pointing is important due to the destructive nature of the step. Imaging using bright-field optical contrast enables identification of the layer observed based on the material and thin film contrast. As the device scales down with the different nodes, the extremely thin metal and via layers below M3 can be easily removed if the optical contrasts cannot differentiate the different layers. In the sub-14 nm nodes, the traditional brightfield contrast do not provide enough information to accurately determine the layer observed. In this work, we present advanced contrast techniques employing such as polarization differential interference contrast with circularly polarized light to provide a dynamic contrast that is rich in information to precisely identify the layer observed.

II. Experimental Results

To differentiate and end point the desired layer of interest, two commercially available AMD Ryzen processor chips with14 nm and 7 nm die samples were manually polished and then examined under an optical microscope (Zeiss Axioscope 5 Mat). Various contrast methods were utilized to enhance the examination process. The same sample was then examined under a scanning electron microscope (SEM) to corroborate the results.

Brightfield contrast provides a uniform illumination of incident light perpendicularly onto the sample surface, Fig. 1A. This is suitable for showing amplitude objects (colored or stained). However, the resultant glare from the surface often makes it a challenge when underlying material edges need to be identified. In this example of a 14nm delayered die, the vertical and horizontal metal lines appeared in the same color, which makes identification of the metal layer between them a difficulty, Fig. 1B. The contrast however differentiates the edges of metal layers observed in a bluish colour from the dielectric/via layers. The thickness of the low-k dielectric layers can be differentiated moderately using this contrast as observed in Fig. 1B.

Fig. 1. (A) Reflected light brightfield beampath [8], and (B) its imaging of a delayered 14 nm die.



In darkfield contrast, light is incident on the sample at a highly oblique angle, with a dedicated reflector cube and objective with a special mirror assembly, Fig. 2A. Only the diffracted light is detected, while the background is dark. Surface topographies like scratches and edges show strong contrast in this method. The surface features, dust particulates, SRAM and logic regions of delayered die, in this example, is clearly observed and differentiated. However, the differentiation of the different metal layers in the form of alternating vertical and horizontal metal lines is not clear, Fig. 2B.

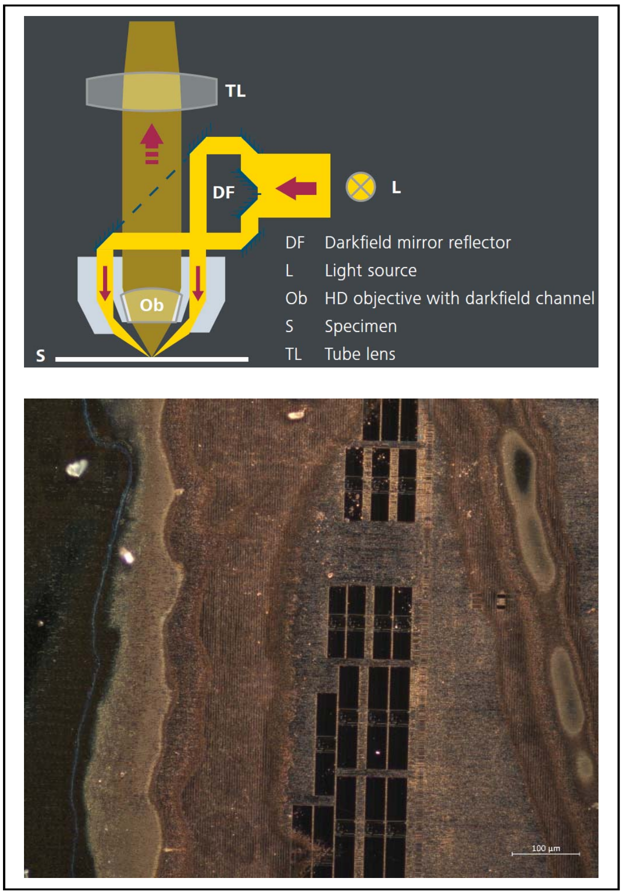


Fig. 2. (A) Reflected light darkfield beampath [8], and (B) its imaging of a delayered 14 nm die.

The linear geometrical features of the metal lines strongly influence scattering and reflection of polarized incident light that allows adoption of polarization based contrast to differentiate the horizontal and vertical orientation of the metal interconnect layers. A set of crossed polarizer and analyzer is required to perform polarization microscopy, Fig. 3A.

The polarization contrast with the same polarization alignment between the polarizer and analyzer is shown in Fig. 3B. The cross-polarized contrast with an orthogonal alignment of the polarizer and alignment is shown in Fig. 3C. The polarization contrast is strongly enhanced and shows difference between the horizontally aligned layers with vertically aligned layers. However, the contrast observed is similar to thicker dielectric layers and doesn't display any variations due to the presence of the dielectric layer or its varying thickness due to the mechanical polishing. In the case of the cross-polarized contrast, the differentiation of the various layers is not strongly visible with this condition of operation, Fig. 3C.

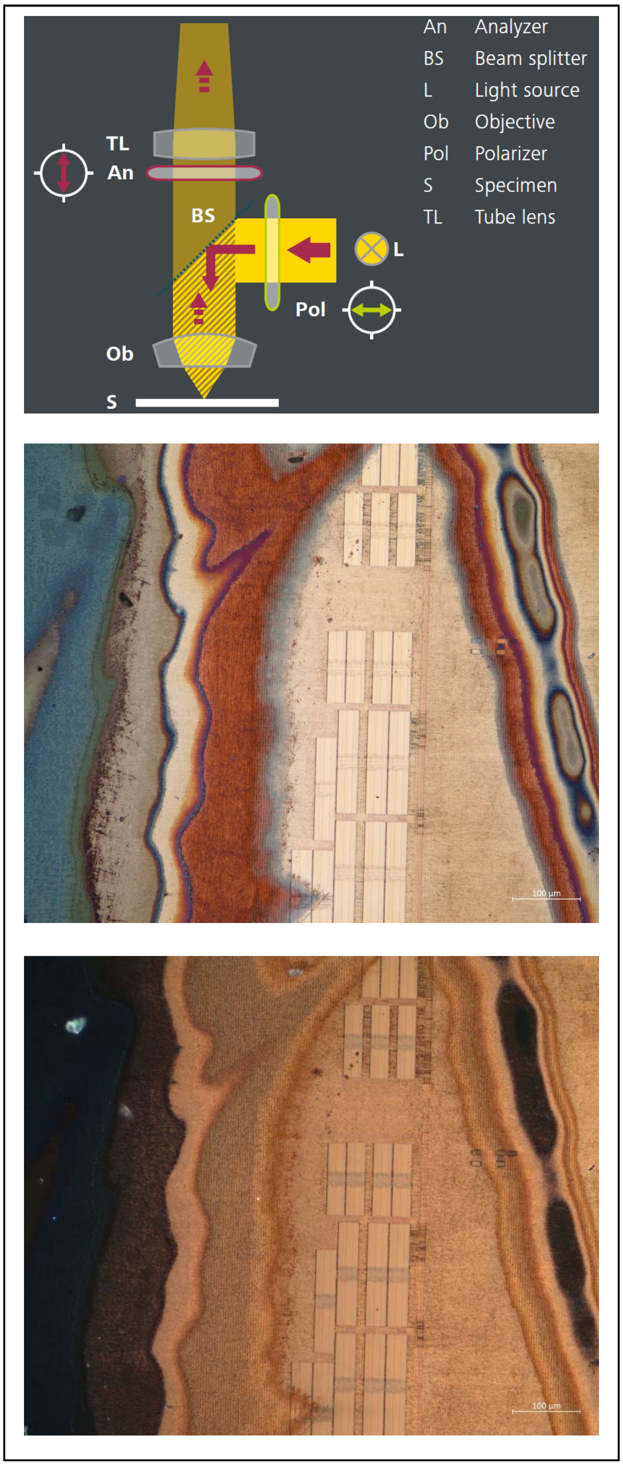


Fig. 3. (A) Reflected light cross polarisation beampath [8] and its imaging of a delayered 14 nm die with (B) The polarizer and analyzer are aligned in the same direction and (C) The polarizer and analyzer are orthogonally aligned.

Where classic brightfield, darkfield or polarization techniques falls short of contrast, C-DIC technique can be used to not only to detect very fine structures and defects, but also to display them in high contrast. The difference between DIC and C-DIC is that the latter uses circularly polarized light, resulting in more rich contrast and better resolution.

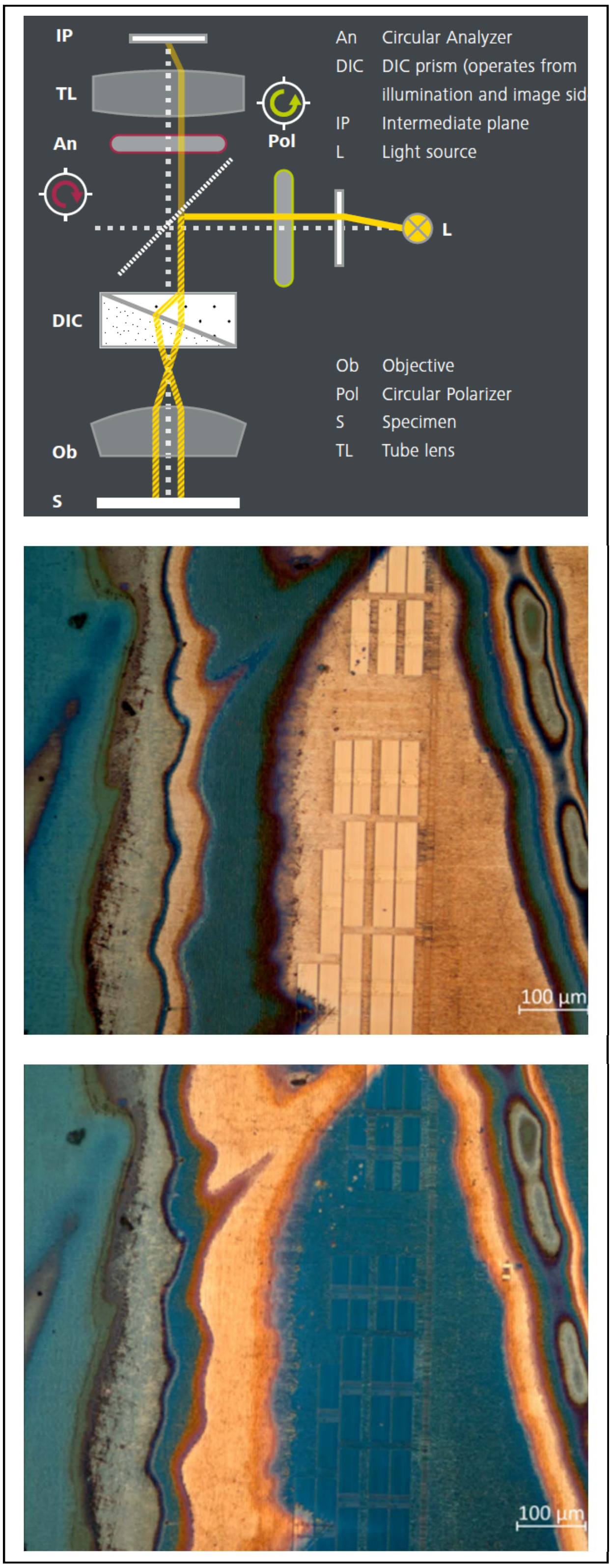


Fig. 4. (A) Reflected light C-DIC beampath, circular polarizer (= polariser + λ/4 plate), circular analyzer (= analyzer + λ/4 plate) [8], (B) its imaging of a delayered 14 nm die, and (C) upon rotation of C-DIC prism in azimuthal direction.

In addition, there is no need to rotate the specimen, as the rotating of the C-DIC prism would achieve the effect of changing the shear direction, Fig. 4A. This gives rise to the unique advantage of retaining defect orientation with respect to the specimen. Fig. 4B presents the same sample region imaged with the C-DIC contrast revealing a vivid set of colours showing the vertically oriented metal layers in blue while the horizontally oriented metal layers in orangish-yellow colors. There is a strong delineation of the metal layer edge, via-dielectric layer. As the prism is rotated in azimuthal direction to rotate the polarization orthogonal, the inversion of colours to the horizontally oriented layers is easily observed, Fig.4C. The ability to distinguish the various metal layer orientation, metal layer edges and via/low-k dielectric layers simultaneously represents a significant advantage over the tradition DIC technique.

III. Discussion

As compared to amplitude objects, phase objects have little difference in intensity or color. Differential interference contrast (DIC), based on Nomarski, is a widely used method to provide high contrast images of phase objects, that have height differences, or objects that are linear structures with geometrical alignment with the incident polarization direction or difference in material-specific phase shifts of adjacent structures. A beam of linearly polarized light is first separated by DIC prism into two orthogonally polarized light beams. Both beams are sheared laterally at an order of magnitude close to the resolving limit. When the beams hit the sample surface of differing heights, varying geometric orientation of features that align with the polarization or material-specific phase shifts, one beam must travel further than the other, resulting in a phase difference. After reflecting off the surface, the two beams then recombine in the prism and undergo interference in the analyzer. This produces intensity changes at the sites where the feature height, orientation or material-index changes. Maximum contrast, with a shadow cast appearance, can be achieved in only one preferred direction, with the step height perpendicular to the shear direction. On the other hand, if the step height is parallel to the shear direction, it might not be visible at all. Thus, a rotating stage is needed for DIC [9].

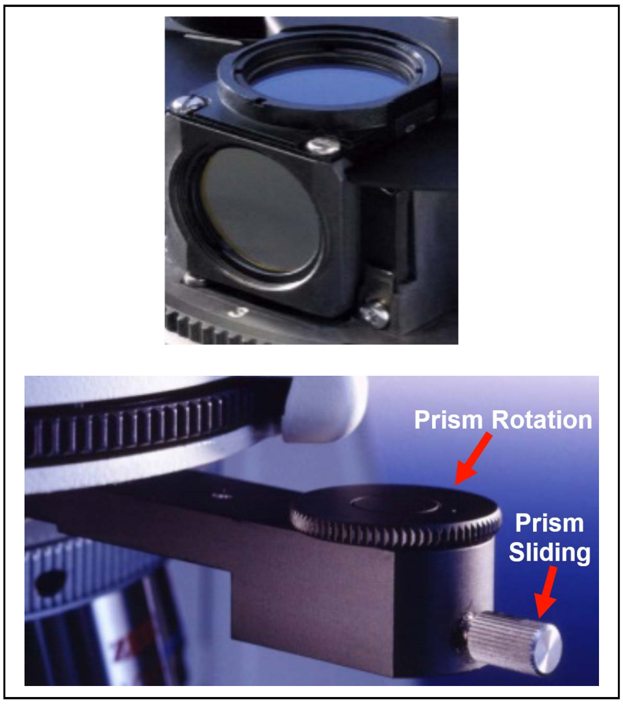


Fig. 5. C-DIC Reflector Cube & C-DIC Prism Slider [10].

C–DIC is a Zeiss unique contrast method. As compared to conventional DIC (Nomarski), C-DIC utilizes circular polarized light, instead of linearly polarized light. The effect of this is that when the prism is rotated, the shear direction is rotated, while the specimen stays fixed in position. C-DIC is used only in a Zeiss compound microscope, and consists of a C-DIC reflector cube, and a C-DIC slider in a reflected light setup, Fig.5. Sliding of the prism changes the amount of shear which would determine the resolution (small shear) and contrast (large shear). This technique is highly sensitive to structural orientation of the features under investigation (polarization), material thickness and refractive index (phase) [10].

Fig. 6. Motorized modulator turret, with C-DIC prism, that can be fitted onto Zeiss Axio Imager series of advanced light microscopes [10].

The Zeiss Axio Imager series of advanced light microscopes can be fitted with motorized modulator turret, with prisms of specific contrast methods, Fig.6. Inside this motorized modulator turret, the appropriate C-DIC prism can be swiveled in by pressing buttons to control forward rotation or backward rotation of the turret. The motorized modulator turret has a rotatable "Azimuth" and "Shift" knob, controllable either manually by hand or electronically by software. With the specimen on the stage, the "Shift" knob is turned until the structure of interest can be seen in maximum contrast. The contrast can be optimized by turning "Azimuth" knob on the modulator turret. These would essentially have the same functionality as the C-DIC slider present in the Zeiss standard light microscopes, but with the added-on advantage of being repeatable as the amount of azimuth and shift can be set to a desired value in the microscope software. Thus, the same C-DIC contrast settings can be applied on different specimens and also by different users.

To verify the observed contrast with the actual nanometer scale structures in the metal interconnects, correlative light and electron microscopy has been employed. SEM inspection with a ZEISS GeminiSEM 500 is also performed to corroborate the results of the optical inspection. For this work, a 7 nm die from the AMD Ryzen chip has been used. The sample was mechanically polished to achieve a gradient and varying thickness across the different metal interconnect layers. The sample is inspected using the ZEISS Axioscope 7 with different contrast mechanisms as shown in Fig. 7. The light microscopy images are seen in Fig. 7A-C and the corresponding electron microscopy image is shown in Fig. 7D. Fig. 7D highlights the different orientation of the metal layers across 3 different layers of metal, via/dielectric layers.

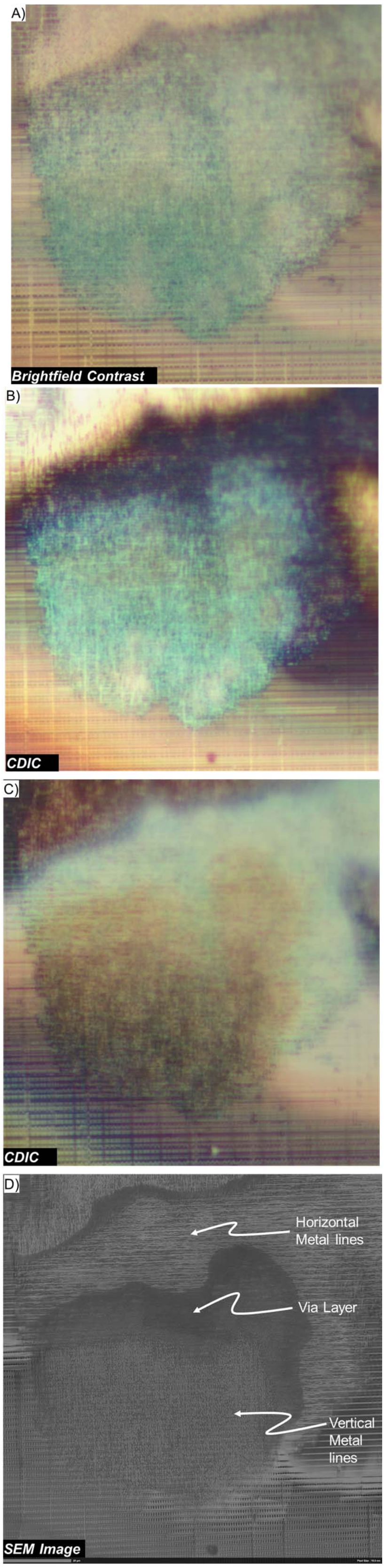


Fig. 7. (A) Bright-field optical image of a delayered 7 nm AMD Ryzen 3700X die and (D) SEM image of the same region highlighting different layers in the same ROI. Scale bar is 20 microns. (B&C) C-DIC provides complementary information to identify the different layers.

Under brightfield contrast, it is almost indistinguishable across the two metal and via layers to accurately determine if the desired layer in the BEOL stack has been reached at the ROI for defect inspection, Fig. 7A. The C-DIC contrast provides an image that clearly delineates the two metal layers, Fig. 7B and adjusting the prism further to improve the contrast further provides information about the via layer as well, Fig. 7C. These images clearly provide a fast and accurate method to determine the metal layer orientation and also discern the ultra-low k thin layers without the need for frequent SEM inspection.

Thus, C-DIC can be used to complement the SEM inspection, in a faster way. In order to ensure the repeatability of this examination with C-DIC contrast, the motorized modulator turret can be used. The desired amount of azimuth and shift corresponding to the best contrast of the different layers is noted, and then set in the microscope software.

IV. Summary

The distinct vertical and horizontal metallic features and the thin via-dielectric layers can be imaged with better resolution and contrast, using polarization and phase contrast available from C-DIC, as compared to the traditional brightfield contrast.

The C-DIC imaging module provides a novel contrast mechanism to end-point and precisely identify different layers in the semiconductor die BEOL. This provides a unique value add in the semiconductor FA workflow to streamline delayering and optical inspection step for improved efficiency and higher throughput.

ACKNOWLEDGMENT

We would like to express our thanks to Dion Zudhistira and Teo Wee Siang (Advanced Micro Devices (AMD), Singapore) for providing assistance in sample preparation. We would also like to thank Dr Thomas Rodgers (Carl Zeiss Research Microscopy Solutions) for his valuable feedback and support.

References

[1] V. Sankaran, C.M. Weber, K.W. Tobin “Inspection in Semiconductor Manufacturing”, Webster’s Encyclopedia of Electrical and Electronic Engineering, vol. 10, pp. 242-262, Wiley & Sons, NY, NY, 1999.

[2] K. Wells, G. Chen, M. Derstine, S. Lange, and D. Shortt, “Extending optical inspection to the VUV,” in 2017 International Conference on Frontiers of Characterization and Metrology for Nanoelectronics (FCMN), D. G. Seiler, ed., pp. 92–101, NIST, (Monterey, CA USA), 2017

[3] R. Attota, B. Bunday, V. Vartanian, “Critical dimension metrology by through-focus scanning optical microscopy beyond the 22nm node”, Appl. Phys. Lett. 102, p. 222107, 2013

[4] J.H. Lee, “Through-focus scanning optical microscopy with adaptive optics”, Proceedings of the SPIE, Volume 10585, id. 105850C 10 pp. (2018).

[5] R. Zhou, C. Edwards, C. Bryniarski, M. F. Dallmann, G. Popescu, and L. L. Goddard "White-light interferometric microscopy for wafer defect inspection", Proc. SPIE 9336, Quantitative Phase Imaging, 93362P (11 March 2015)

[6] R. Zhou, C. Edwards, A. Arbabi, G. Popescu, L. L. Goddard, “Detecting 20 nm Wide Defects in Large Area Nanopatterns Using Optical Interferometric Microscopy”, Nano Lett. 2013, 13, 8, 3716-3721

[7] R. Zhou, C. Edwards, G. Popescu, and L. L. Goddard "9nm node wafer defect inspection using visible light", Proc. SPIE 9050, Metrology, Inspection, and Process Control for Microlithography XXVIII, 905017 (2 April 2014)

[8] Light Microscopy Contrast Methods for Materials Research, EN_41_050_030, CZ 07-2019, Carl Zeiss Microscopy GmbH

[9] C–DIC: a new microscopy method for rational study of phase structures in incident light arrangement, Rainer Danz, Peter Gretscher, Thin Solid Films 462–463 (2004) 257– 262

[10] A unique light microscopy contrasting method makes it visible: C-DIC (circular differential interference contrast) in reflected light, Tom Calahan, EN_42_013_231, CZ 04-2017, Carl Zeiss Microscopy LLC USA