CRADA 0560 – Final Report

Direct To Digital Holography

Prepared by
Philip R. Bingham and Kenneth W. Tobin

Abstract

In this CRADA, Oak Ridge National Laboratory (ORNL) assisted nLine Corporation of Austin, TX in the development of prototype semiconductor wafer inspection tools based on the direct-to-digital holographic (DDH) techniques invented at ORNL. Key components of this work included, testing of DDH for detection of defects in High Aspect Ratio (HAR) structures, development of image processing techniques to enhance detection capabilities through the use of both phase and intensity, and development of methods for autofocus on the DDH tools.

Statement of Objectives

The purpose of this Cooperative Research and Development Agreement (CRADA) between UT-Battelle, LLC (Contractor), and *n*Line Corporation (Participant), was to provide defect and high aspect ratio inspection (HARI) technologies for semiconductor wafer production at 130 nm feature sizes and smaller. The nLine Corporation, in collaboration with ORNL and other JV (joint-venture) partners, was the recipient of a NIST ATP award for development of a pulsed laser deep ultra-violet (DUV) digital holographic inspection system. The ORNL portion of the collaboration resulted in this CRADA between nLine and ORNL. Because it is a phase-sensitive and heterodyne technology, the proposed direct-to-digital holographic (DDH) inspection tool is capable of six orders of magnitude more sensitivity than any other optical technology for detection of small defects or inspection of high aspect ratio structures. The advantage increases as the defect or structure becomes smaller relative to the wavelength of light used for inspection. Also, because it is an optical inspection technology amenable to larger area illumination and imaging (as opposed to a particle beam), this DDH technology has the possibility of high throughput for HARI relative to SEM (scanning electron microscopy) or other optical technologies. The objective of the NIST ATP project was to demonstrate proof-of-concept deep ultra-violet laser (nominally between 266 nm and 193 nm) direct to digital holography as a volume inspection tool for the semiconductor industry.

The work performed at ORNL was proof-of-concept work to demonstrate wafer die inspection at parameters relevant to DUV, and to assistance with the software necessary to acquire, process, and analyze measurement data and control the prototype system. Key tasks performed in this CRADA include testing of defect detection in HAR structures, development of image processing techniques for improved detection, and research and development of autofocus methods.

Benefits to DOE Office's Mission

The project addresses DOE mission in two major ways. First, the development of new inspection tools for the semiconductor manufacturing environment has the potential for reductions in energy consumption during manufacturing. Second, this project supports the development of new technical business in the United States and moves technology developed at a DOE lab into the commercial sector.

Technical Discussion of Work Performed

This project centered around three major areas: Testing of defect detection on HAR structures using the 532nm visible alpha tool (VAT) built at ORNL, Development of image processing methods to further enhance defect detection, and development of autofocus methods for the DDH tools.

HAR Defect Detection on the VAT

With the VAT built under a previous CRADA with nLine, ORNL performed an array of testing on this 532nm tool to characterize performance and determine any systematic noise concerns that would also appear in the DUV tool being developed in the NIST ATP project. Figure 1 shows an example of detection results on a HAR wafer.

From this example, we find that the phase results provided by DDH are enabling the detection of defects below the spatial resolution of the illumination wavelength. Additional tests were performed on intentional defect array wafers provided by International SEMATECH. These tests varied parameters on the VAT system and compared defect detection performance in the various test conditions. Figure 2 shows the detection results from one of these tests.

Image Processing Development for Defect Detection

Image processing development was performed in several areas including refocusing, noise filtering, and thresholding. In the defect detection studies, we quickly learned that the systems will need different setup parameters such as threshold levels depending on the types of semiconductor structures being inspected. One key area of development in this subtask involved the study of methods to segment these various structure types automatically using wavelet decomposition techniques. Figure 3 shows a composite result from this work in which the various regions of the die are segmented. The segmented image would be used to identify the defect detection recipe that should be used for each segment on the wafer.

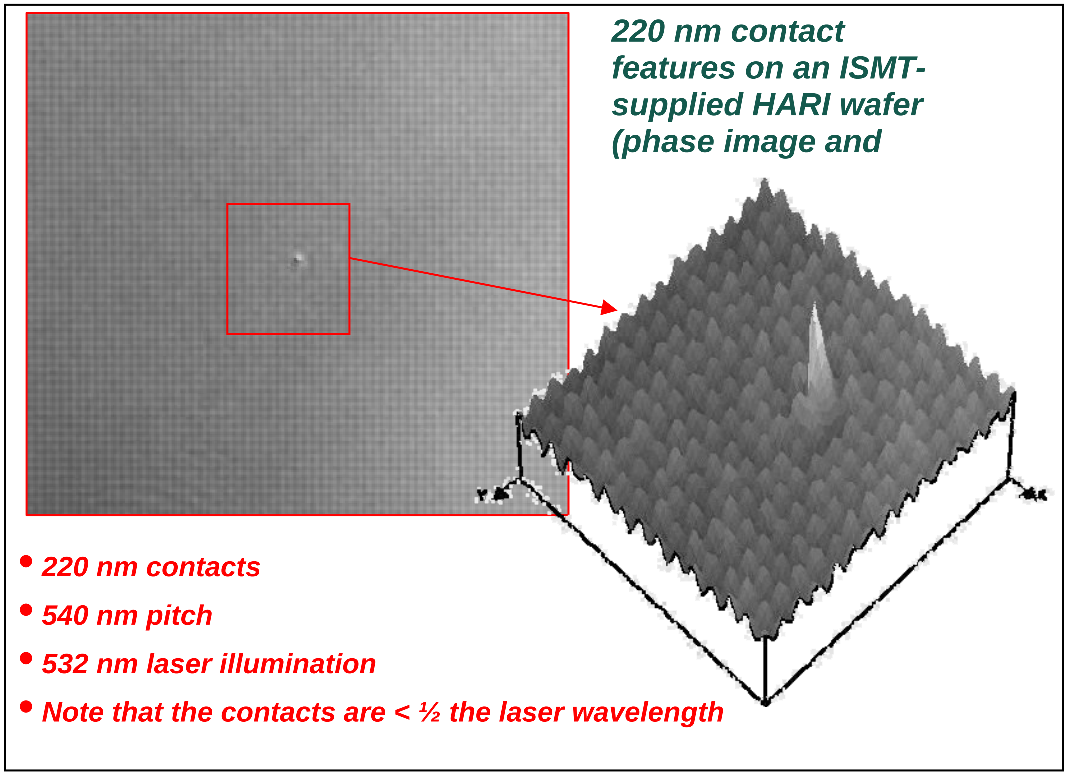

Figure 1. Example of defect detection on a HARI test wafer.

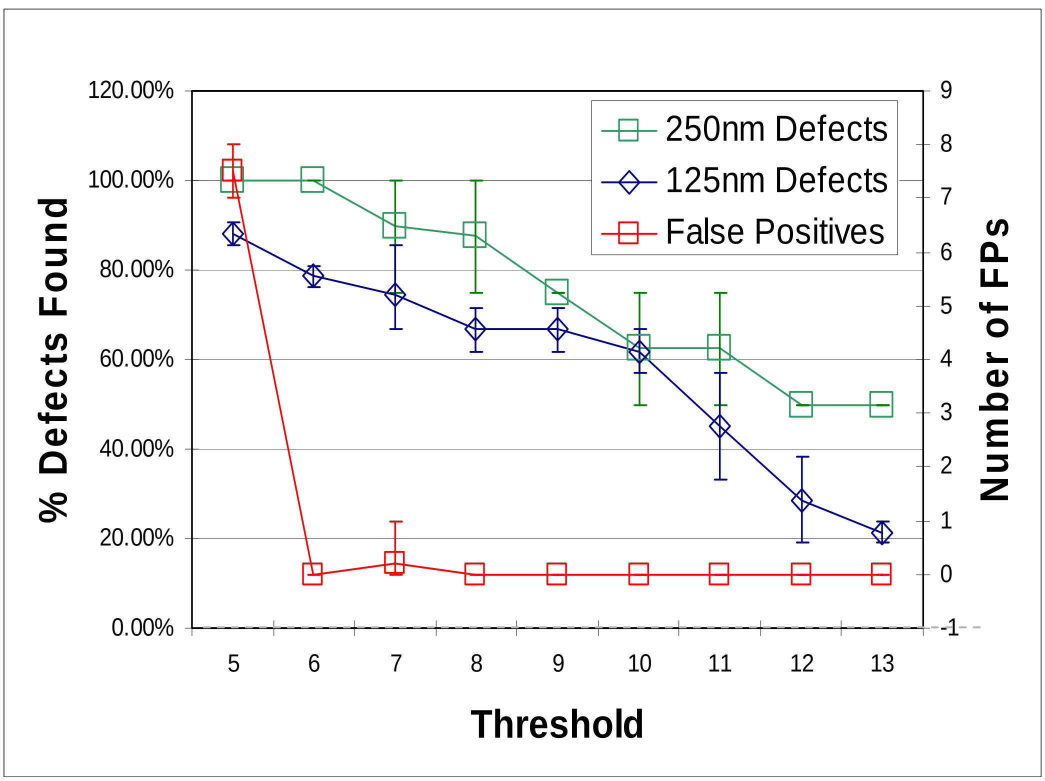

Figure 2. Detection results on International Sematech Intentional Defect Array test wafer.

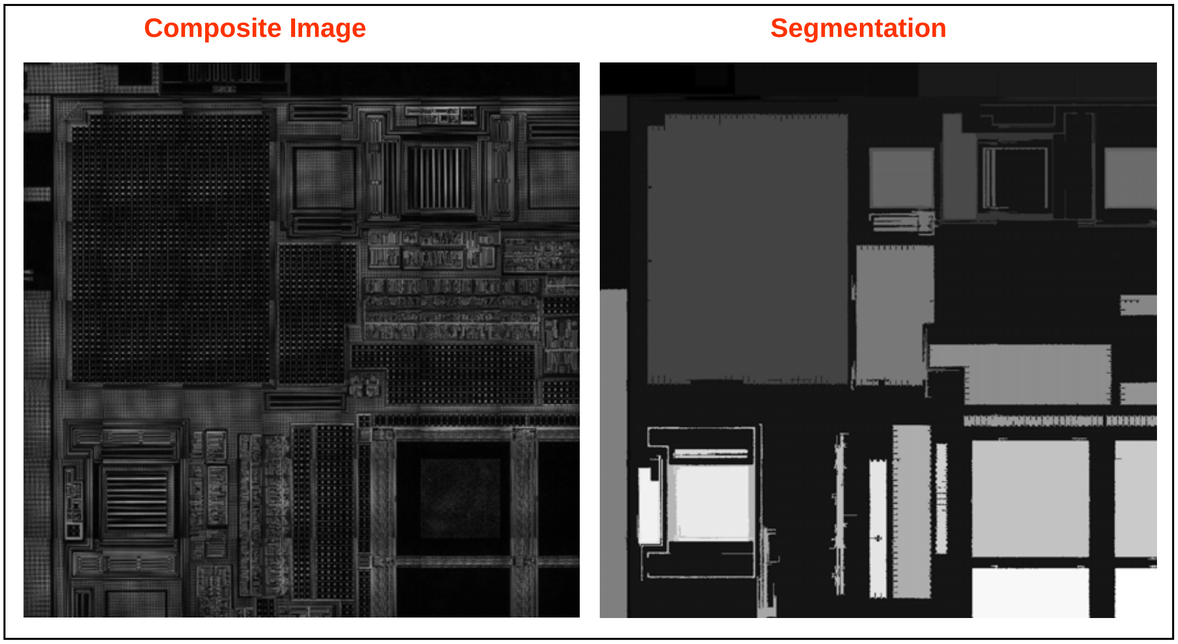

Figure 3. Segmentation results from

Autofocus development

The original VAT tool developed at ORNL uses a point confocal distance gauge to determine distance to the wafer and keep the system in focus. In testing, we found that this gauge is affected by the small structures on the wafers that are smaller than the wavelength of light used by the distance gauge. ORNL developed methods to determine safe regions to use the distance gauge. Figure 4 shows a map generated by this method. By mapping the contour of the wafer by this method before beginning defect detection, detection results were improved through better focus.

One advantage of capturing a full complex wave through the DDH method is the fact that the image can be refocused through a straightforward multiplication by a phase map in the frequency domain. Likewise, one should expect that two complex images can be divided to capture this phase wedge and determine focus difference between these two images of similar structures at different focus levels. ORNL performed some basic studies into image based autofocus for the DDH tools. One particularly interesting result is shown in Figure 5. In this test, the focus was varied on a single location of the wafer. Division of these images in the frequency domain produced the rough shaped results shown in the plots. The smooth lines in the plots correspond to the phase plates expected for the given focus change. The real differences match the expected differences fairly well. Based on these results, we feel that we could bring the images back into focus within 100-200nm.

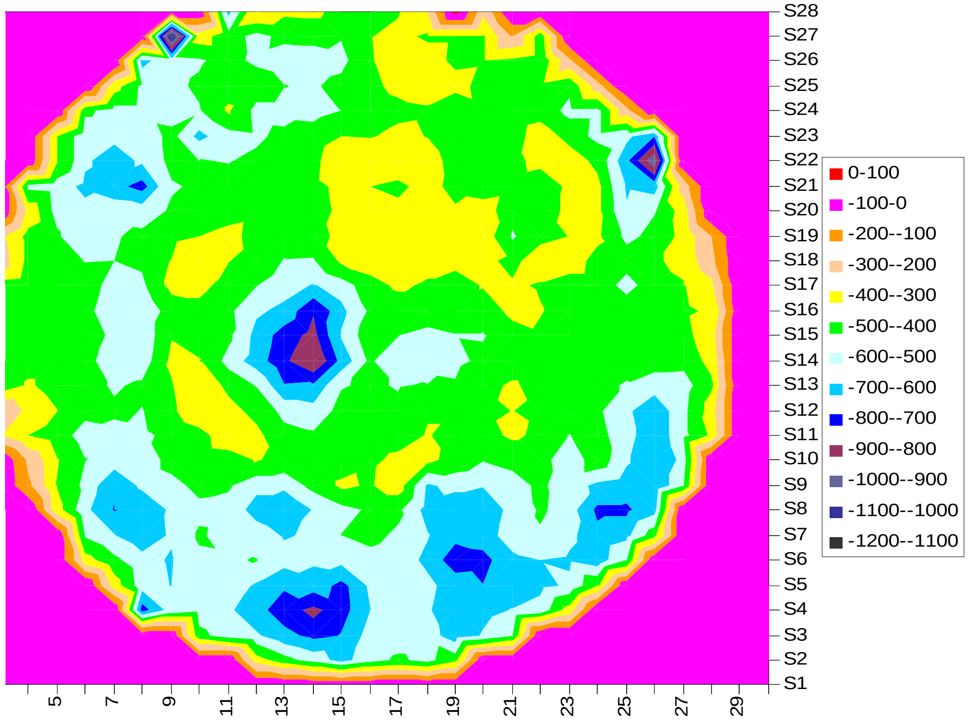

Figure 4. Height map of a 200mm wafer on the VAT tool.

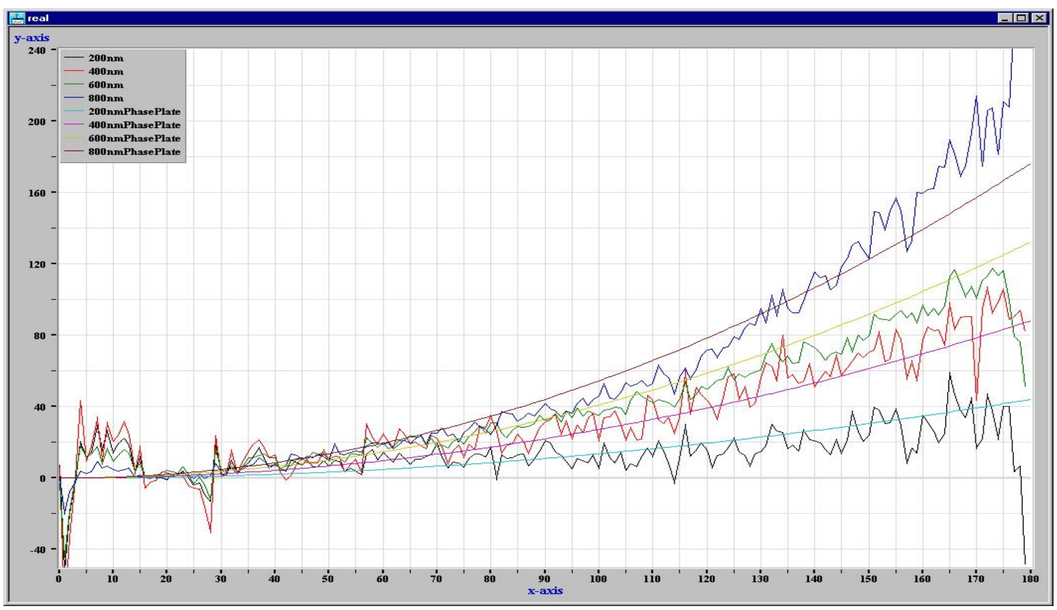

Figure 5. Image based autofocus with direct focus difference determination.

Subject Inventions (As defined in the CRADA)

- Hanson, G.R., Bingham, P.R., Tobin, K.W., "Spatial-heterodyne interferometry for reflection and transmission (SHIRT) measurements", U.S. Patent 6,999,178 issued February 14, 2006.
- Price, J.R., and Bingham, P.R., "Fused off-axis object illumination direct-to-digital holography with a plurality of illumination sources," U.S. Patent 6,963,406, November 8, 2005.
- Hanson, G.R., Bingham, P.R., Simpson, R.T., Voelkle, E., and Karnowski, T.P.,"Technique for Optaining Two-Wavelength Differential-Phase Direct-to-Digital Heterodyned Holograms", ORNL ID No. 0933, April, 2003, (Patent pending).
- Hanson, G.R., and Bingham, P.R., "Recording Multiple Spatially-Heterodyned Direct to Digital Holograms in One Digital Image", ORNL ID No. 0933.1, June 2003, (Patent pending).
- Hanson, G.R. and Bingham, P.R., "Faster Processing of Multiple Spatially-Heterodyned Direct to Digital Holograms", ORNL ID No. 0933.2, U.S. Patent 7,116,425, October 3, 2006.
- Hanson, G.R., Bingham, P.R., Tobin, K.W., "Spatial-heterodyne interferometry for transmission (SHIFT) measurements", U.S. Patent 7,119,905, October 10, 2006.

Commercialization Possibilities

nLine corporation has been the main push in commercialization of this technology. However, due to fluctuations in the semiconductor market and slow development of the tool such that the semiconductor industry now needs higher resolutions than can be reached with the 266nm system, nLine is no longer pursuing this technology for semiconductor inspection. Three other possible areas of development are inspection of photolithographic masks used in wafer production as they have features several times larger than the wafers, inspection of Micro Electro Mechanical Systems (MEMS), and quantitative phase microscopy for biological imaging.

Plans for Future Collaboration

ORNL is still in contact with the original investors for nLine and hope to pursue further development of the technology for MEMs inspection and lithography mask inspection.

Conclusions

This CRADA was very successful in obtaining goals outlined in the original SOW. With this CRADA, ORNL assisted nLine corporation in improving the defect detection capabilities of the DDH systems for HAR structures.