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FOR THE DEPARTMENT OF ENERGY

Final CRADA Report

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For

CRADA No. ORNL 591

With

Nova Measuring Instruments, Ltd.

For

Development of a Whole-wafer, Macro-scale Inspection Software Method for Semiconductor Wafer Analysis

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Abstract

This report describes the non CRADA-protected results of the project performed between Nova Measuring Systems, Ltd., and the Oak Ridge National Laboratory to test and prototype defect signature analysis method for potential incorporation into an in-situ wafer inspection microscope. ORNL's role in this activity was to collaborate with Nova on the analysis and software side of the effort, wile Nova's role was to build the physical microscope and provide data to ORNL for test and evaluation.

Introduction

This report describes the collaborative work performed between Nova Measuring Instruments, Ltd. (Nova) and the Image Science & Machine Vision (ISMV) Group of the Oak Ridge National Laboratory (ORNL) to develop an analysis method for semiconductor Automatic Defect Classification (ADC) and Spatial Signature Analysis (SSA). The ISMV Group has developed novel implementations of both the ADC and SSA technologies, which are licensable as background intellectual property (IP). Nova has developed an optical-based inspection tool that is able to scan whole wafers and detect photolithography related defects. Since ORNL has already developed a background intellectual property for the SSA technology and has applied experience technology in ADC, Nova requested that a CRADA partnership be established to assist them in the development of analysis methods for tier new macro-scale wafer inspection tool.

The prototype analysis and software development was performed by ORNL using images and data obtained by Nova's inspection tool. The development was completed at ORNL's site interactively with Nova. The ORNL software system was developed such that future improvements could be made by Nova personnel. The methodology, e.g., for system training, was desingned to be adaptable to Nova's customers at various manufacturing sites. The procedure used in both ADC and SSA use a defect/signature library containing historical examples of commonly occurring cases at the user site and facilitate training and specification of the system to their particular signature events.

The ISMV Group has been working in the area of semiconductor yield management since 1991. and has developed several patented and patent-pending technologies related ADC, SSA, and Content-based Image retrieval (CBIR) in support of new methods and technologies for semiconductor yield management in the semiconductor manufacturing area.

Statement of Objectives

The objective of this project was to adapt and integrate ORNL's SSA and ADC methods and technologies in the Nova imaging environment. ORNL accomplished this objective by modifying the existing SSA technology for use as a wide-area signature analyzer/classifier on the Nova macro inspection tool (whole-wafer analysis). During this effort ORNL also developed a strategy and methodology for integrating and presenting the results of SSA/ADC analysis to the tool operator and/or data management system (DMS) used by the semiconductor manufacturer (i.e., the end-user).

Benefits to the Funding DOE Office's Mission

The Image Science and Machine Vision (ISMV) Group of the Oak Ridge National Laboratory has developed and patented a technology for analyzing distributions of defects that occur during the production of semiconductor wafers [1, 2, 3, 4, 5]. The technology, called Spatial Signature Analysis (SSA), organizes distributions of defects on wafers and sources them back to a potential equipment problems. These distributions of defects are denoted "signatures" based on the analogy to the uniqueness of a human signature and the ability to identify individuals by their penmanship. The carry over to semiconductor manufacturing is that process equipment imparts its own "signature" to the semiconductor wafer during processing. Identifying these unique signatures facilitates the location and isolation of the errant process and allows for the rapid correction of the problem. The result is an increased yield learning rate, and ultimately a faster ramp up of new processes and products. In terms of the DOE energy mission, technologies such as SSA result in semiconductor manufacturing yield improvement and therefore in the reduction of lost products, product re-work, energy consumption, and waste mitigation. Even for a modest yield improvement of 0.1% this equates to a U.S. savings of 7,560 MWhr/yr in electric power consumption. This also equates to a reduction of water usage by 74,270,000 gal/yr. There will also be 663,100 pounds of Sodium Hydroxide not produced, along with 185,700 pounds of other miscellaneous hazardous wastes that are not generated. Although Nova is an Israeli company, the majority of manufacturers who will benefit from their products fabricate semiconductor devices in the United States.

Technical Discussion of Work Performed by All Parties

This section presents the results of the final tasks performed by ORNL for Nova. These tasks were focused on the development of software that would support tests and evaluation of the SSA-methods for analyzing whole wafer defect patterns and are described as follows.

Testing Program for Modifying Feature Values

The purpose of this task was to develop source code that could be used to test additional SSA features, particularly Fourier coefficients, without forcing us to rewrite large sections of code. To perform this task, we wrote a set of executables that take SSA signatures and modify them to add new features. We also wrote software that took an SSA clustering result and measured a set of new features on the clusters. These new features are Fourier coefficients, invariant moments, and a special invariant moment measurement that is made on the wafer map before clustering is performed (thus, every cluster in the wafer has the same values for these features.)

Actual Test of Additional Features

The purpose of this task was to test SSA performance using the new features. We used the TestPSL program developed during previous work. The TestPSL program takes a large library, or "master prototype signature library (PSL)", and builds a new library using random selections from the classes in the library. This new random library is trained and then used to classify the remaining members of the master PSL. The training results are saved. In our previous work, we randomized the library 128 times to help test for robustness of features and libraries.

Correct Bug in TESTPSL Program

We also found and corrected a bug that the PSLs produced by the TestPSL program which caused the ssa-tool software to crash. We found the source of this bug; it was the misuse of methods in the TestPSL program. We corrected this bug in TestPSL, but it was corrected after our tests were run, so it is possible that the resulting PSLs from TestPSL are corrupted. However, we have found that the MendPSL utility we developed adequately allowed the user to circumvent the problem and still use the libraries.

Summary of Software Routine Definitions

The following is a summary of the source code produced by ORNL fro Nova that was used to prototype and test the methods developed for macro-level wafer inspection. This code and test results constituted our final deliverable to Nova. The full report containing performance results (CRADA protected information) was provided to Nova in our final project report delivered directly to Nova in Novmeber 2001.

GenSsaFeatures.C A UNIX-based program that performs clustering, generates features on objects, and writes the feature values to a spreadsheet file. (The file is in Excel CSV format.) This routine also creates SSA result files for each wafer file.

GenFeaturesScript A UNIX script that calls GenSsaFeatures for multiple Nova Data Files (NDF).

add_fourier_ftrs_script2 MATLAB routine that adds Fourier features, invariant moments, and whole-wafer invariant moments to a spreadsheet file. While doing this it must read labeled defect images created in SSA and perform feature extraction. This is slightly modified from the add_fourier_ftrs_script which was used in earlier testing of new features.

MergeCsvFeatures A UNIX-based program that takes the SSA result files and the new features in a spreadsheet file and merges them into new result files.

MergeScript A UNIX-based script that calls MergeCsvFeatures.

UpdatePSLScript A UNIX-based program that updates a PSL file by using updated result files created from MergeCsvFeatures.

editLibrary A UNIX-based program that reads a PSL file and writes a new PSL file that has the same signatures but uses a subset of the original PSL's features. The features to be retained are selected by an input text file.

TestPSL A test program using SSA methods that reads the master PSL, then creates a random PSL based on input parameters. The random PSL is trained, and then it classifies the vectors from the master PSL that were not included in the random PSL. The results are recorded along with the random PSL. Classes are merged (i.e. Curvilinear Focus Spot and Amorphous Focus Spot are merged into one class, Focus Spot) based on a remapping file.

compile_confusion_csv A MATLAB routine for summing multiple confusion matrices created by TestPSL. These confusion matrices are each in the form of a CSV spreadsheet file. This MATLAB routine receives a text file that lists the input CSV files.

compile_confusion_script A MATLAB script for calling compile_confusion_csv for a number of feature sets.

Subject Inventions

Nova licensed the SSA technology from International SEMATECH (ISMT), Austin Texas. This technology was developed by ORNL for ISMT in the mid-1990's. The technology is jointly owned by ISMT and ORNL and licensing is managed by ISMT, with royalty sharing between ORNL and ISMT. SSA was initially developed to address the need to intelligently group, or cluster, wafermap defects together into spatial signatures that can be uniquely assigned to specific manufacturing processes. Standard industry practice has been to apply proximity clustering that results in a single event, e.g., a long scratch, being represented as many unrelated clusters. The result is an inherent inability to provide a meaningful cluster classification. SSA performs data reduction by clustering defect data together into extended spatial groups and assigning a classification label that reflects a possible manufacturing source. The grouping of defects into human-recognizable events is achieved through the application of morphological image processing techniques coupled with a fuzzy inferencing method that connects extended spatial patterns based on human-level rules. Once the grouping is complete, a non-parametric, fuzzy k-nearest neighbor (k-NN) classifier is used to label the event. The class label is drawn from a prototype signature library (PSL) that contains representative training data. The following U.S. Patent applies:

Tobin, K.W., Jr., Gleason, S.S., Karnowski, T.P., and Sari-Sarraf H., "Automated Defect Signature Analysis for Semiconductor Manufacturing Process Improvement", U.S. Patent No. 5,982,920, January 7, 1997.

Commercialization Possibilities

Nova is continuing to evaluate and integrate the SSA technology as prototyped and demonstrated by ORNL through the CRADA. Their ultimate goal is to produce an integrated hardware and software in-situ inspection tool that will be sold through process equipment manufacturers to semiconductor device manufacturers. As of the conclusion of this CRADA, Nova was experiencing a severe slow-down in its activities related to the development and commercialization of the macro-level inspection tool due to a critical down-turn in the world-wide semiconductor economy.

Plans for Future Collaboration

Plans for continued or future collaborations between Nova and ORNL are on hold pending improvements in the world-wide semiconductor economy.

Conclusions

Nova supplied ORNL with sufficient synthetic and real measurement data from their early tool development effort to complete and deliver our prototyping and analysis software for their use. Although we had a limited number of training samples, and had to rely on synthetic modifications of training samples, we have shown that SSA has good performance when working with the Nova defect files. We have explored adding new features to improve that performance. To do so, we generated software that enables us to quickly generate new features in MATLAB or C, add them to the existing features, and test them using the SSA classification engine. In doing this we found that our additional features generally caused poorer performance. However, when comparing the confusion matrix data from these feature tests, we found that Fourier descriptors may have helped reduce the confusion between some critical signature classes, which was the original goal. However, overall there are more errors and there are more unknowns. We are not sure why that is the case, but the fact that more features could cause poorer performance indicates that improvements could be made to SSA's ability to select features for us. To this end, if this effort continues in the future, we may experiment with statistical methods for purposes of feature selection and feature weighting. The ISMV Group has used this previously for feature selection in pattern recognition, and it may be beneficial when used here. The framework we have developed for testing new features and combinations of features will make such future experiments easy to accomplish. Although Nova was very pleased with the results provided them by ORNL under the limited funding situation that evolved around this effort, future work between Nova and ORNL will be dependent on a significant improvement in the semiconductor industry economy and a return to profitability by Nova as a company.

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