Direct to digital holography for semiconductor wafer defect detection and review

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ABSTRACT

A method for recording true holograms (not holographic interferometry) directly to a digital video medium in a single image has been invented. This technology makes the amplitude and phase for every pixel of the target object wave available. Since phase is proportional to wavelength, this makes high-resolution metrology an implicit part of the holographic recording. Measurements of phase can be made to one hundredth or even one thousandth of a wavelength, so the technology is attractive for finding defects on semiconductor wafers, where feature sizes are now smaller than the wavelength of even deep ultra-violet light.

Keywords: digital holography, semiconductor wafer defects, semiconductor metrology, high aspect ratio inspection (HARI)

1. INTRODUCTION

A method of recording optical holograms directly to a charge coupled device (CCD) camera or any other suitable video camera with a digital computer interface to any digital storage medium (RAM, hard drive, tape, recordable CD, etc.) has been invented and patented[1] by Oak Ridge National Laboratory (ORNL) and InterScience, Inc., and an exclusive license for semiconductor process diagnostics has been granted to nLine Corporation. No film, no plates, no developer, no darkroom and no waiting are required for this Direct to Digital Holography (DDH). The actual object wave (phase and amplitude for every pixel) is extracted and stored using a fast Fourier transform (FFT). Additionally, the object wave phase or amplitude may be displayed directly on a two-dimensional display. The system is suitable for recording and replaying holographic images in real time or storing them for replay later. Since a hologram stores amplitude and phase, with phase being directly proportional to wavelength and optical path length, this direct to digital holography can serve as an extremely precise measurement tool for verifying shapes and dimensions of precision components, assemblies, etc. Similarly, the ability to store the true holograms digitally immediately provides a method for improved forms of digital holographic interferometry. Holograms of the same object, after some physical change (stress, temperature, micro-machining, etc.), can be subtracted from one another (direct subtraction of phase) to calculate a physical measurement of the change (phase change being directly proportional to wavelength). Similarly, two ostensibly identical objects can be compared and deviations identified and measured by subtracting their respective holograms.

This new holographic technology is promising for semiconductor wafer lithographic inspection and measurement tools. Demonstration of the technology for wafer high-aspect-ratio inspection (HARI) and defect inspection using a deep ultra-violet (DUV) laser is complete for many materials, and prototype inspection tools have been designed and built. The demonstration work has proven feasibility and compatibility of the DDH DUV tool with the required optics and many semiconductor materials (organics remain unproven). The DUV technology is built on a firm base in visible optical technology, which is described further below.

Traditional methods of holography have used film or holographic plates (glass plates with a photographic emulsion optimized for holography) to record the hologram. Replay of the hologram has only been possible using lasers (or in some cases white light) and the original recorded hologram or a duplicate of it, in an analog method. These analog methods are slow, cumbersome, and expensive. There is also no easy way to reduce them to electronic signals that can be transmitted and replayed at another location. As a practical matter, it has always been necessary to send hard copy. Worse still, the time delay involved in processing the film prevents the use of holography and its variants in many situations. Even if the expense of the classical holographic system itself was tolerable, the time requirement and low throughput caused by the necessity of processing the film introduces delays that are intolerable.

While digital holographic interferometry (often practiced in the form of electronic speckle pattern interferometry) has been around for a number of years, until now it has not been possible to extract the original object wave. The reason that true digital holography has not been developed until now is that the resolution of digital video cameras or cameras adaptable to digital media is not good enough to record the very high spatial frequencies inherent in classical side-band holograms. Several techniques that overcome this difficulty have been combined to allow recording of holograms and all of their spatial frequencies up to the inherent holographic resolution of the recording camera for Fourier transform hologram analysis. This will be discussed further below, but if the recording media (e.g., CCD camera) resolves 100 line-pairs/mm, the holographic resolution will be approximately 33 line-pairs/mm (a line-pair being a line and space pair) for highly correlated images (repetitive content), or 50 line-pairs/mm for images with low correlation (random content). This limit is increased by any magnification that is used. For a camera resolution of 100 line-pairs/mm, the hologram resolution will be approximately 330 line-pairs/mm if a magnification of 10 is used or 33,000 line-pairs/mm at a magnification of 1000 (if not diffraction limited). Similarly, the spatial resolution will be decreased by any de-magnification of the original image on to the recording camera.

2. DIRECT TO DIGITAL HOLOGRAPHY DETAILS

Denis Gabor invented holography.[2] Modern sideband (heterodyne) holography was invented by Leith and Upatnieks.[3,4] The present invention combines the use of high resolution video cameras, very small angle mixing of the holographic object and reference waves (mixing at an angle that results in at least two pixels per carrier frequency/sideband fringe), imaging of the object at the recording (camera) plane, magnification of the object as necessary for the required spatial resolution, and Fourier transform analysis of the heterodyne (side-band) hologram to make it possible to record holographic images (images with both the phase and amplitude recorded for every pixel). Additionally, an aperture stop must be used in the back focal plane of one or more lenses involved in focusing the object, to prevent aliasing of any frequencies higher than can be resolved by the imaging system (aliasing is thoroughly described in the literature and placing aperture stops in the back focal plane of a lens to limit the spatial frequencies present is also well described and well understood). No aperture is necessary if all spatial frequencies in the object are resolvable by the holographic sideband imaging system. Once recorded, it is possible to replay the holographic images as 3-D phase or amplitude plots on a two-dimensional display. To illustrate the hardware concepts that have been combined to allow digital recording and replay of holograms, a schematic of a classical sideband holography system and a schematic of a simple direct to digital holography system are presented as Figures 1 and 2 below.
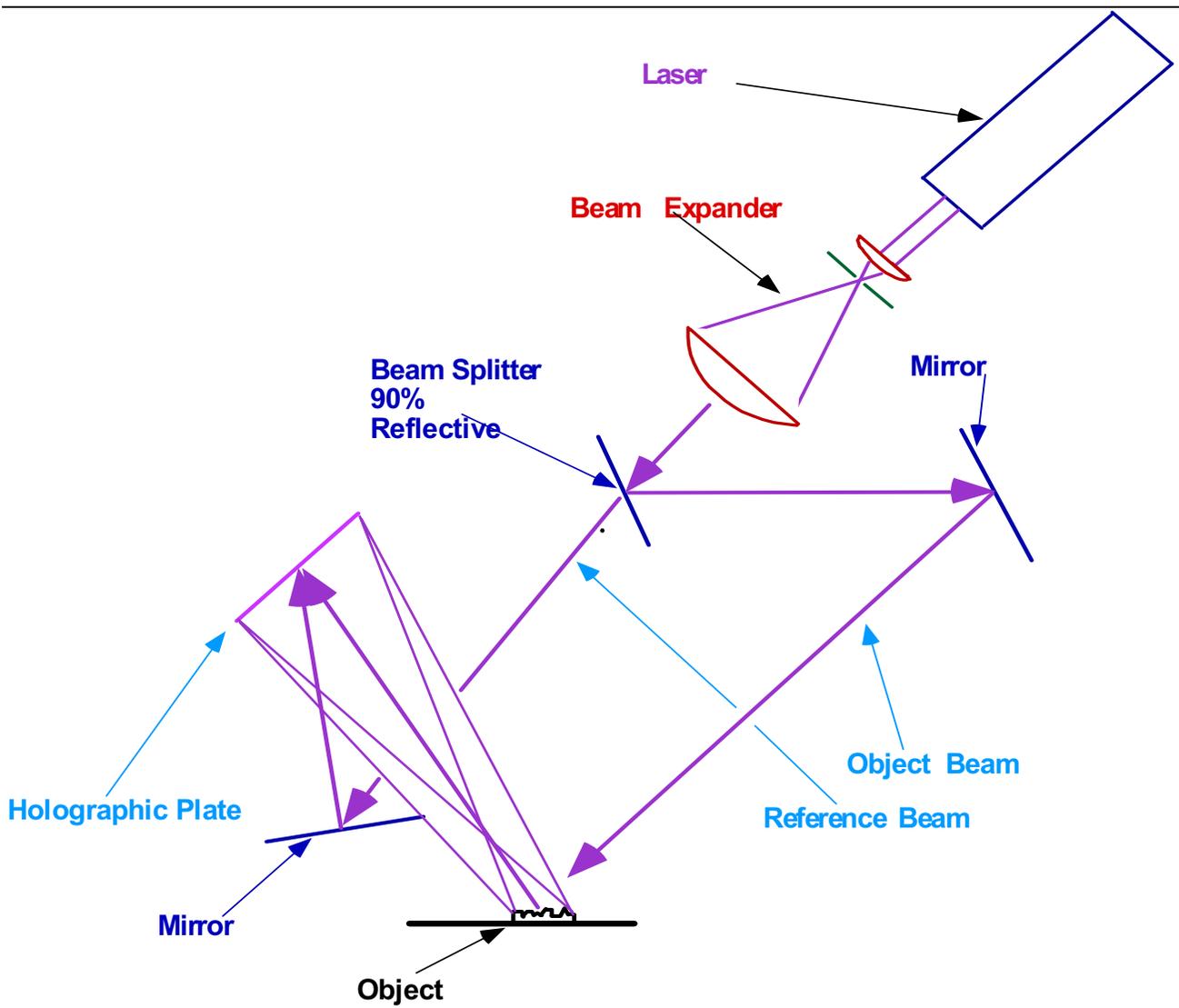
Laser

Beam Expander

Beam Splitter
90%
Reflective

Mirror

Holographic Plate

Object Beam

Reference Beam

Mirror

Object

Figure 1: Classical (Leith & Upatnieks) Sideband Holography System

Direct to Digital
Holography System Schematic
(10/96)
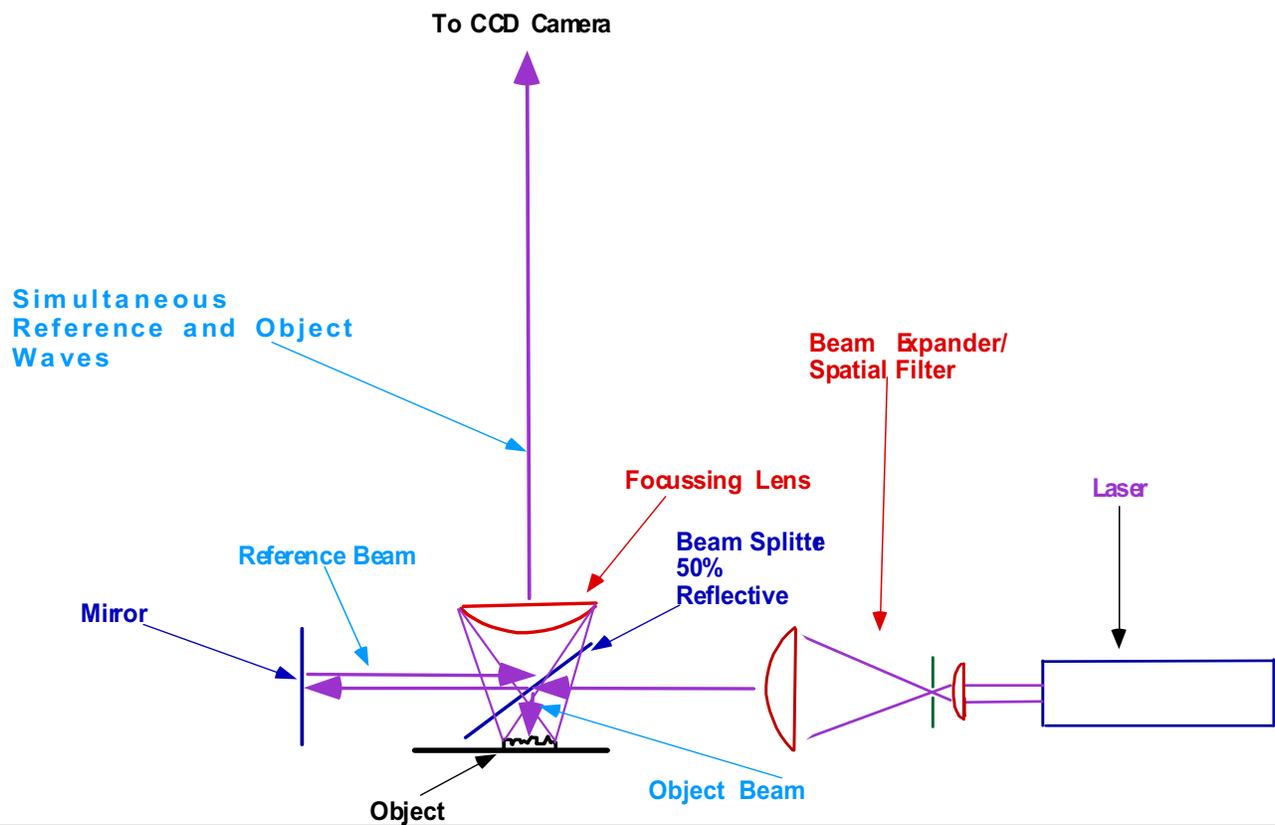
To CCD Camera

Simultaneous
Reference and Object
Waves

Beam Expander/
Spatial Filter

Focussing Lens

Laser

Reference Beam

Beam Splitter
50%
Reflective

Mirror

Object Beam

Object

Figure 2: Direct to Digital Holography Schematic

Comparing Fig. 1 and Fig. 2, it can be seen that the chief differences which allow a CCD camera to record the hologram, rather than using film or a photographic plate, are:

1. Use of a high-resolution CCD camera (in this case 1.4 Mpixels, but CCD's over 60 Mpixels are already available) rather than photographic emulsion.

2. Use of what we call a "Michelson" geometry. Note the geometrical relationship of the beamsplitter, reference beam mirror, and CCD and its resemblance to a Michelson interferometer geometry. This geometry allows the reference beam and the object beam to be combined at a very small angle (the reference beam mirror is tilted to create the small angle that makes the spatially heterodyne or sideband fringes for Fourier analysis of the hologram).

3. Use of a focusing lens to focus the object on to the focal plane of the CCD. This lens also provides magnification or demagnification, as required, by using lenses of different focal length and adjusting the spatial geometry (ratio of object distance to image distance). The diffraction pattern of a point interfering with a plane wave can be described by a spherical function which has increasingly close fringes as the distance from the center of the pattern increases. As these fringes get closer and closer together, they are unresolvable by a video camera. Worse yet, the interaction of these point diffraction patterns from a complex object creates an impossibly dense and complicated pattern, that cannot be anywhere resolved by a video camera. Focusing the object on the recording plane eliminates these diffraction patterns, so that modern high-resolution video cameras can record holograms with the desired spatial fidelity.

4. Magnifying or demagnifying the image as required to achieve the desired spatial resolution adjusts the spatial resolution of the hologram. In general at least two carrier frequency fringes must be placed across the optical resolution (Rayleigh resolution) in order to separate the carrier sideband from the autocorrelation. For strongly correlated (very repetitive pattern) objects three carrier frequency fringes must be placed across the optical resolution to prevent the autocorrelation from bleeding into the carrier sideband. Thus the lens numerical aperture (NA) and CCD pixel size, the requirement of at least two pixels per fringe, and two or three carrier frequency fringes across the optical resolution, determines the required magnification of the optical system.

Methods 1 through 4 above, when combined with Fourier transform software analysis methods adapted from (to be described below) electron holography in a form to be applicable for light-wave holography, allow direct to digital recording and replay of holograms.

Figures 3a and 3b below are pictures of the first DDH system as it was when it became operational in August, 1996.
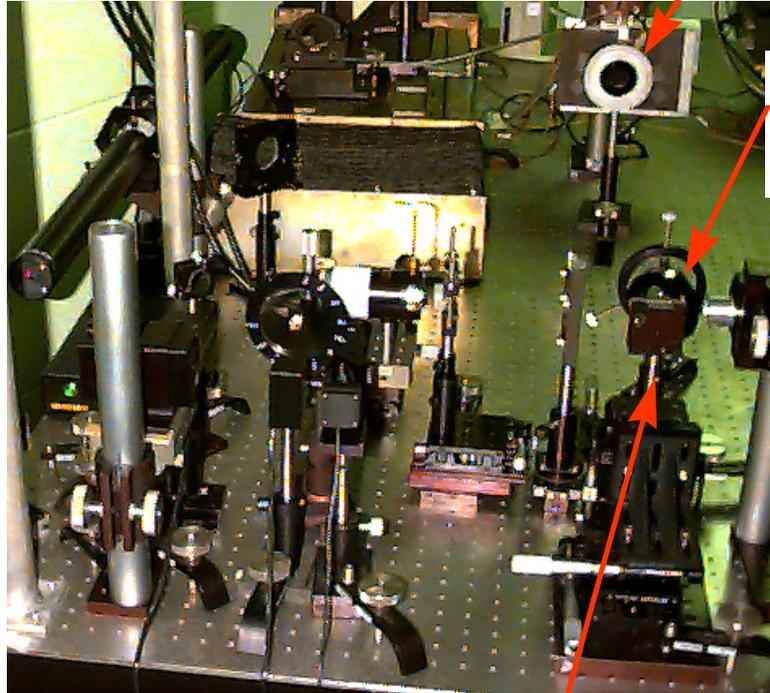
Beam Splitter
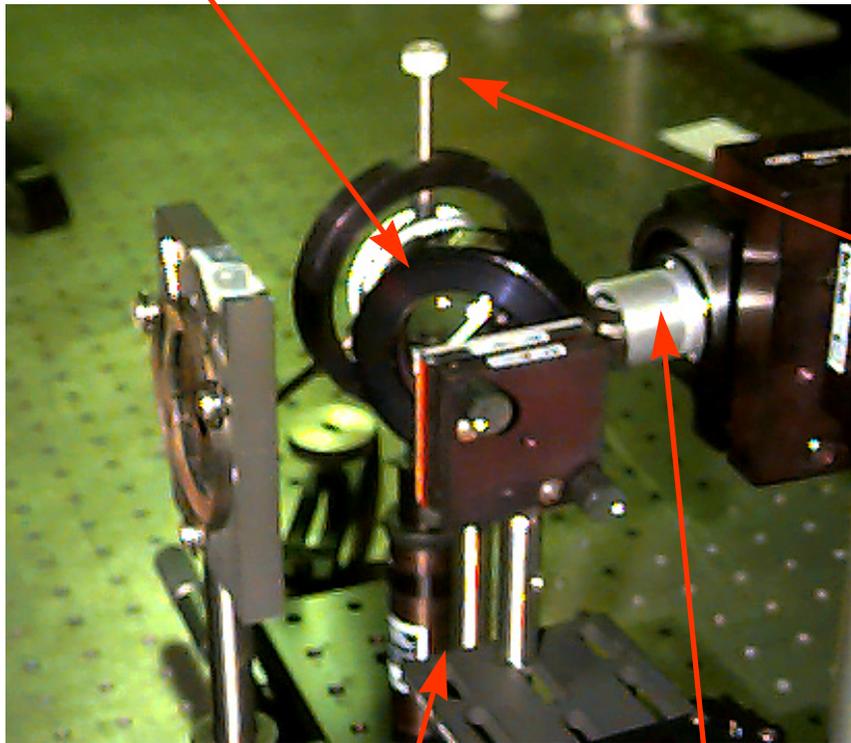
Focusing Lens

Semiconductor Wafer Mount

Reference Beam Mirror

Figure 3a: Close-up photograph of "Michelson" geometry for direct to digital holography

Direct to Digital (CCD Camera)

Michelson Geometry

Object Target Mount

Figure 3b: Overview photograph of original direct to digital holography setup

Figure 4 is a heterodyne (sideband) hologram of a scratch in a mirror (the object in this case). The hologram was made with the direct to digital holography system described and pictured above. The fringes observable in the hologram are due to the interference between the reference and object beams. The reference beam mirror was tilted slightly to create these fringes. It is the presence of these carrier frequency fringes (present in all heterodyne holograms, film or digital) that allows Fourier transform analysis of the hologram to calculate the phase and amplitude for the pixels of the hologram. The Fourier transform analysis itself will be demonstrated and discussed in the next several paragraphs and figures.
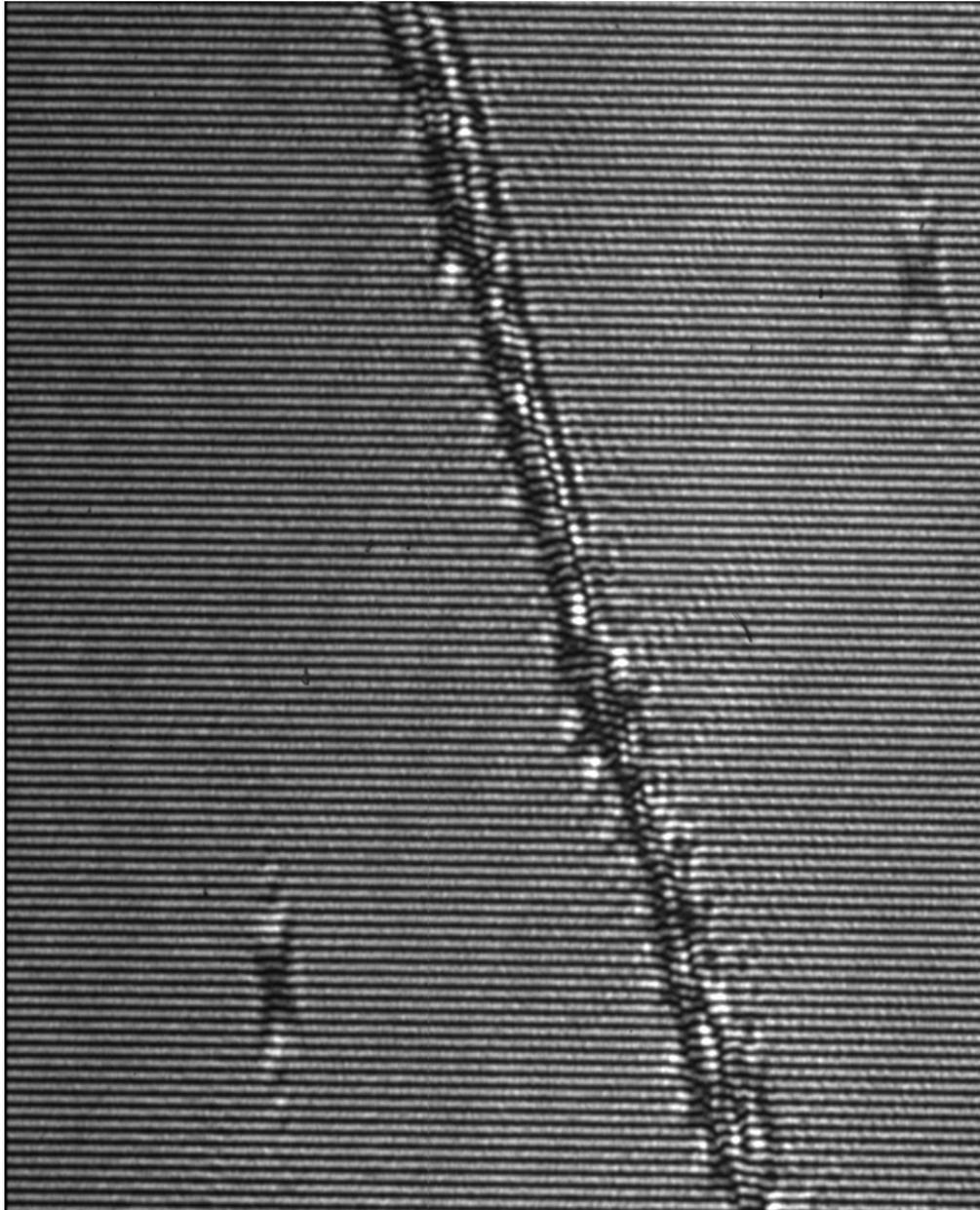
Figure 4: Digitally Acquired Hologram of Scratch in a Mirror

Figure 5 is a graphical plot of the two-dimensional spatial Fourier transform of Figure 4. The x-axis is the spatial frequency axis along the x dimension and the y-axis is the spatial frequency axis along the y dimension. The actual data itself is a matrix of numbers corresponding to the strength of a particular spatial frequency in (f_x, f_y) frequency space. The number and brightness of the white dots shows the strength and position in frequency space of the spatial frequencies present in Fig. 4. It can be seen by examining Fig. 5 that the reference beam fringes act as a heterodyne local oscillator shifting the real and virtual hologram images off-axis and allowing their separation in frequency space. It is known from Shannon's Theorem (or Nyquist's limit) that at least two pixels per fringe are required to resolve a fringe, and to prevent leakage of the autocorrelation into the sideband at least 3 fringes per resolvable object are required to resolve the object in the hologram for highly correlated objects, or two fringes for objects with low correlation. Thus these two limits determine the required magnification of an object and the tilt angle between the reference and object beams in order to resolve an object (spatial frequency) in a hologram.
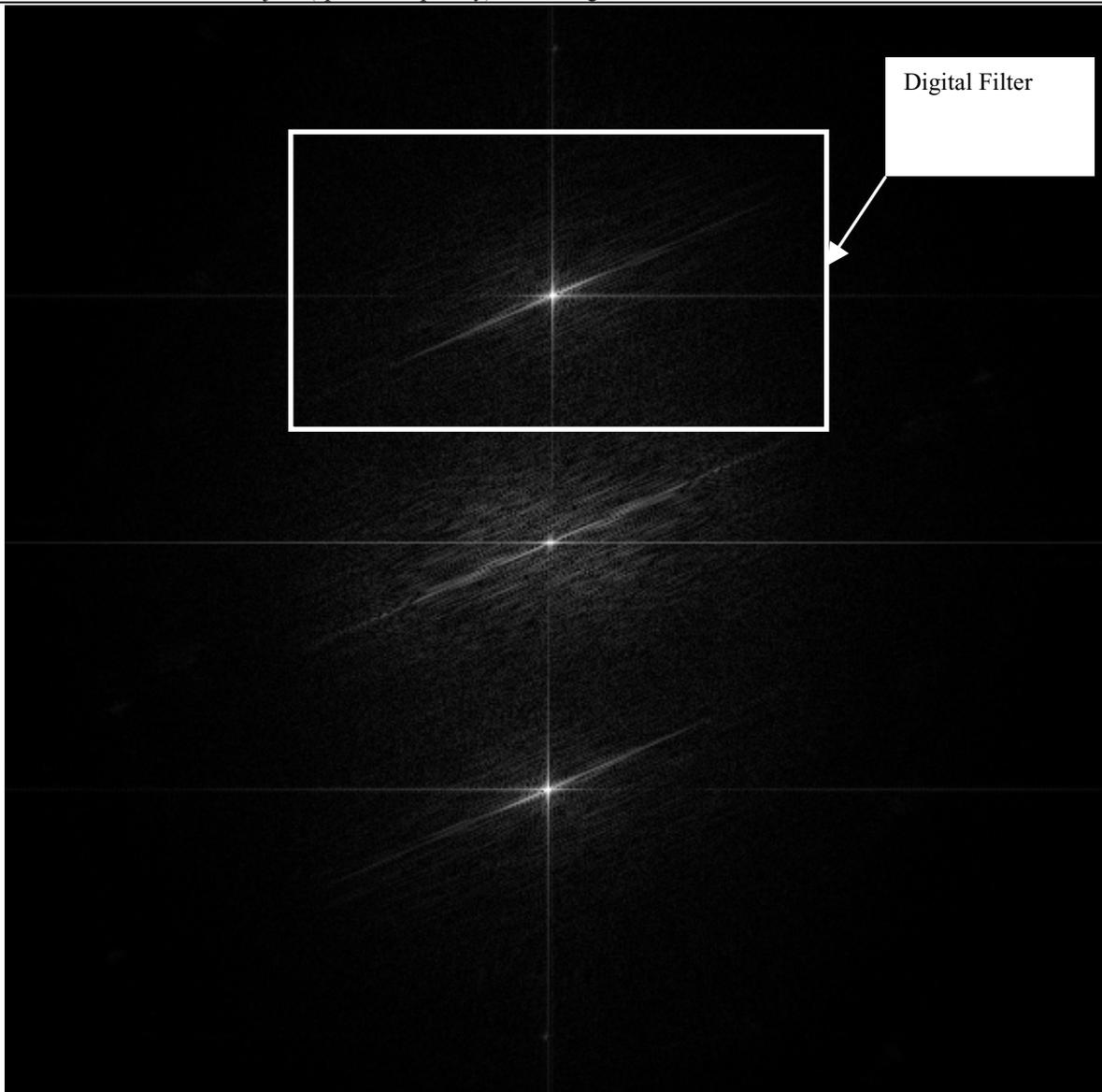

Figure 5: Plot of 2-D spatial Fourier transform of Fig. 4

The data shown in Fig. 5 is analyzed by transforming (shifting) the axes in Fourier space to sit on top of the heterodyne carrier frequency (the spatial frequency caused by the small angle tilt between the object and reference beams), then applying a digital filter (e.g., a Hanning or Butterworth filter) to cut off the signals around the original origin (these are actually the signals resulting from the reference beam interacting with itself and the object beam interacting with itself, and are noise from the hologram point of view), and then performing the inverse Fourier transform. All of this analysis is carried out on a digital computer and can be done in "real time" at a frame rate of about 30 frames per second without too much difficulty. Today, as many as 30 to 100 high performance parallel processors may be required to achieve a frame rate of 30 frames per second. Such a parallel processing system would not even qualify as a "supercomputer" in modern high performance computing, but would rank at the low end of the current high performance computing spectrum.. Computer systems of this size are presently commonly used as large database servers and stock market calculational engines. They are also suitable for short-term low-resolution weather forecasting, and image manipulation and creation for the film industry. It can be expected that such systems will be desktop systems within 6 to 10 years.

Figure 6 shows a replay of the phase data created by performing the described analysis on the data (hologram) from Fig. 5.
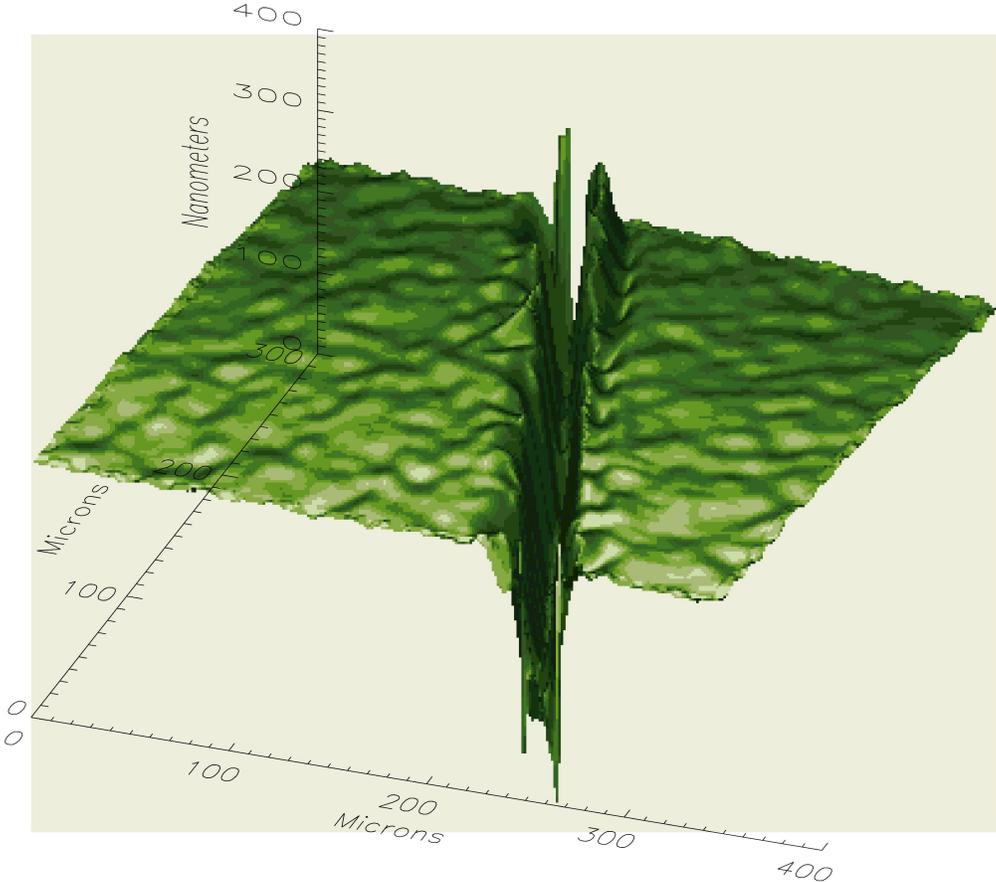

Figure 6: Replay of hologram phase data from hologram of Fig. 4.

The data in Figure 6a is the same data as shown in Figure 6, but now plotted as a gray-scale map rather than shown in 3-D. On this gray scale plot, black represents the lowest dimension, and bright white the highest z-dimension on the plot. A digital line-tool has been drawn across the scratch on the plot, and the data underneath the digital line tool is plotted alongside the gray-scale map as part of Figure 6a. This height data is available for every pixel of the object wave.
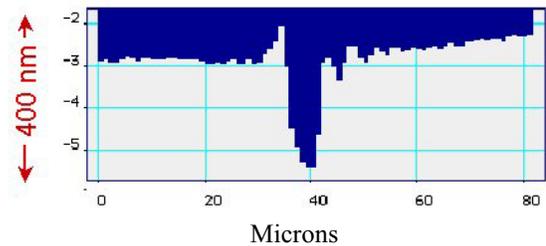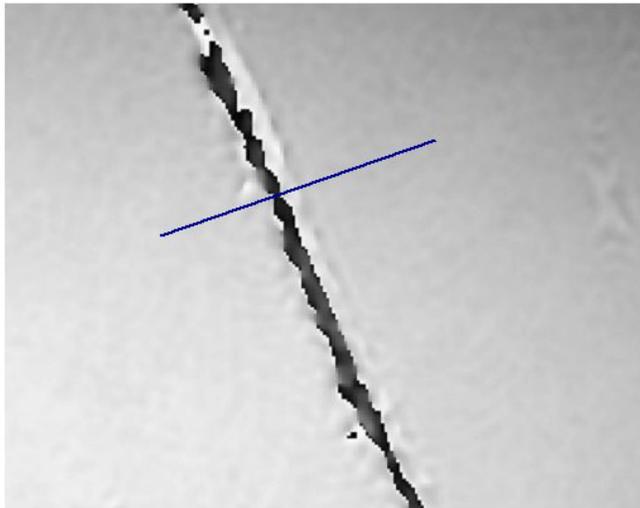
Dimensional Profile showing a
depth of less than 300 nanometers.

Grey-scale phase map of a scratch in a mirror
made from Fourier analysis of hologram.

Figure 6a: Gray-scale phase map. Same data as Figure 6 but plotted as a gray-scale map rather than in 3-D.

3. EXAMPLE WAFER DATA

There are now several nLine Corporation DDH tools operational:

VAT: The Visible Alpha Tool (VAT) using a 532 nm laser, is in use at ORNL as part of a National Institute of Standards and Technology (NIST) Advanced Technology Program (ATP) development program awarded to nLine with ORNL as one of nLine's partners.

DAT: The DUV Alpha Tool (DAT) using a 266 nm laser, is in use for development at nLine also as part of the NIST ATP program work. This tool is used for exploring wafer materials response and development of software algorithms and optical designs.

Fathom: The Fathom^{TM} DUV Alpha Tool was shipped to International SEMATECH (ISMT) on January 7, 2002 and is now in use as part of a Joint Development Project to characterize DDH tool and wafer performance.

Data are becoming available from all three of these tools. Figure 7 is a hologram and resulting 3-D phase map of a chrome on chrome resolution target. The lines and letters on the target are approximately 800 nm in transverse dimension and 100 nm high. This hologram was made at ORNL with a very early version of the DDH tool using a 633 nm wavelength HeNe laser.

800-nm Features 100-nm High

- Raw digital hologram. Note the carrier frequency fringes bending as they pass over surface objects
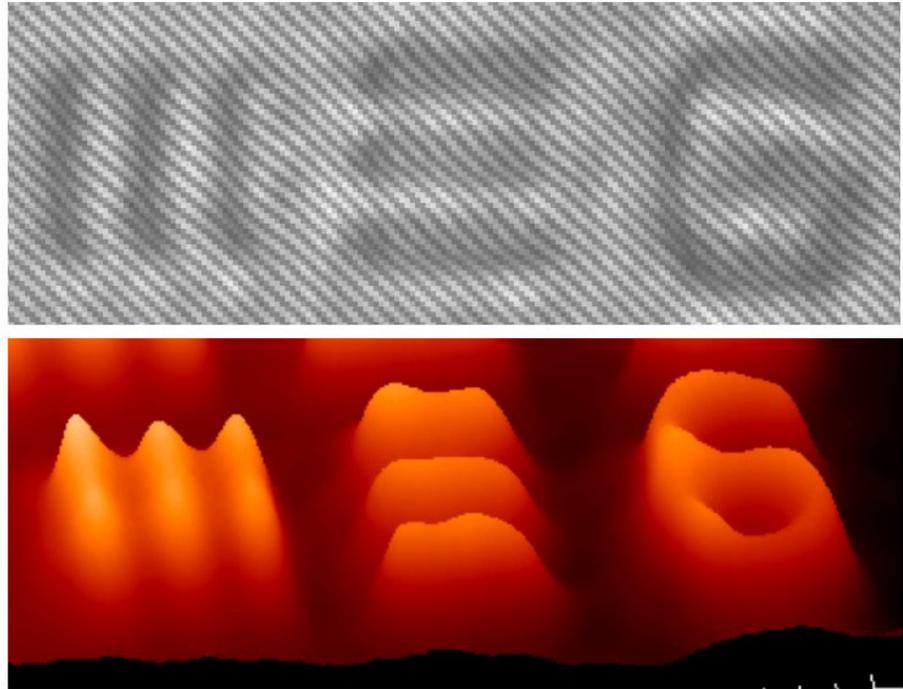
- 3-D Plot of data after Fourier Transform analysis

Figure 7 Raw Hologram and 3-D Phase Map of Chrome on Chrome Resolution Target

The next holographic data, Figure 8, is a gray-scale phase map showing a single bad contact. The raw hologram used to produce the gray-scale phase image was made with the VAT using the 532 nm wavelength laser. The single bad contact is in a sea of approximately 10,000 contacts, but as can be seen from the phase map, the bad contact stands out like a searchlight on a dark night, even thought the rest of the contacts are unresolved by the optics. This wafer was prepared by ISMT as a test wafer for High Aspect Ratio Inspection (HARI) tools.

Single Under Etched Contact, Aspect Ratio 3.4:1
(220 nm contact, 50 nm residual oxide in contact)

Gray-Scale Image: only the defective contact shows up—the thousands of others are unresolved

750 nm

220 nm

50-nm of residual oxide in contact

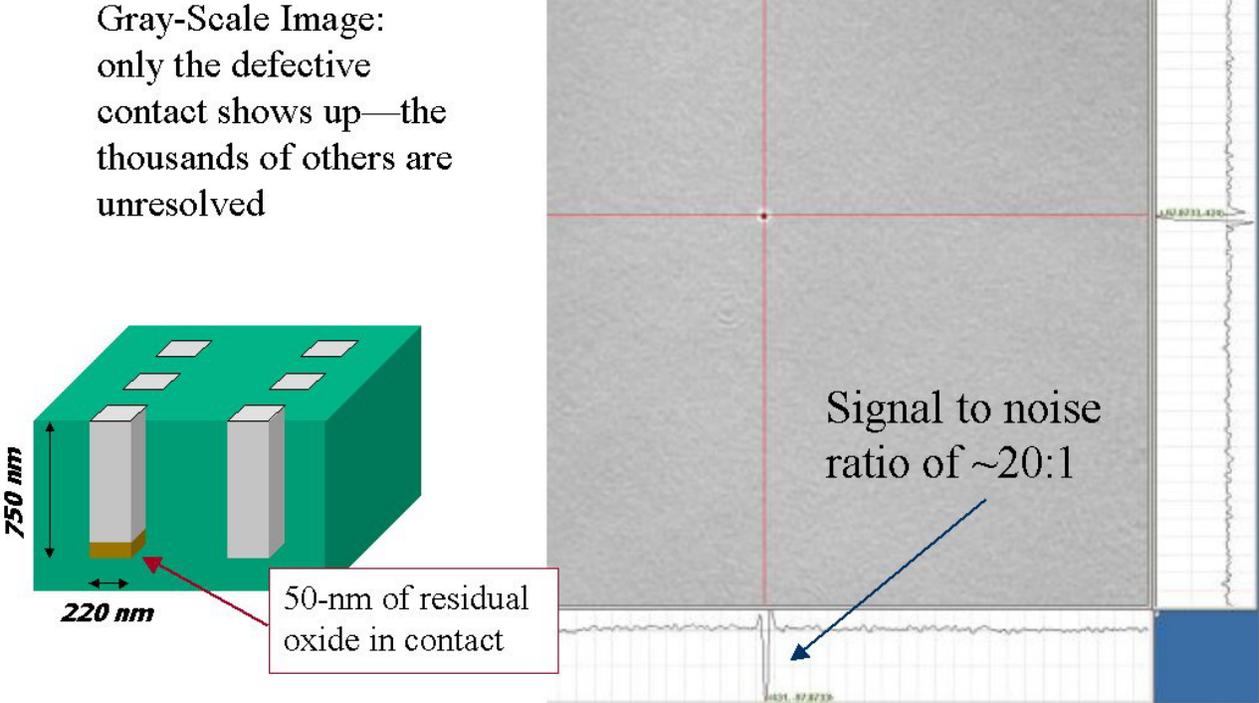Signal to noise ratio of ~20:1

Figure 8: Grey-scale Phase Image of Single Bad Contact in an array of unresolved contacts.

The following phase map, Figure 9, is a gray-scale phase map from another ISMT HARI wafer, this time with an aspect ratio of 6.8:1. In this case the original hologram used to produce the phase map was made with the DAT system at nLine in Austin, TX, using a laser with a 266 nm wavelength.
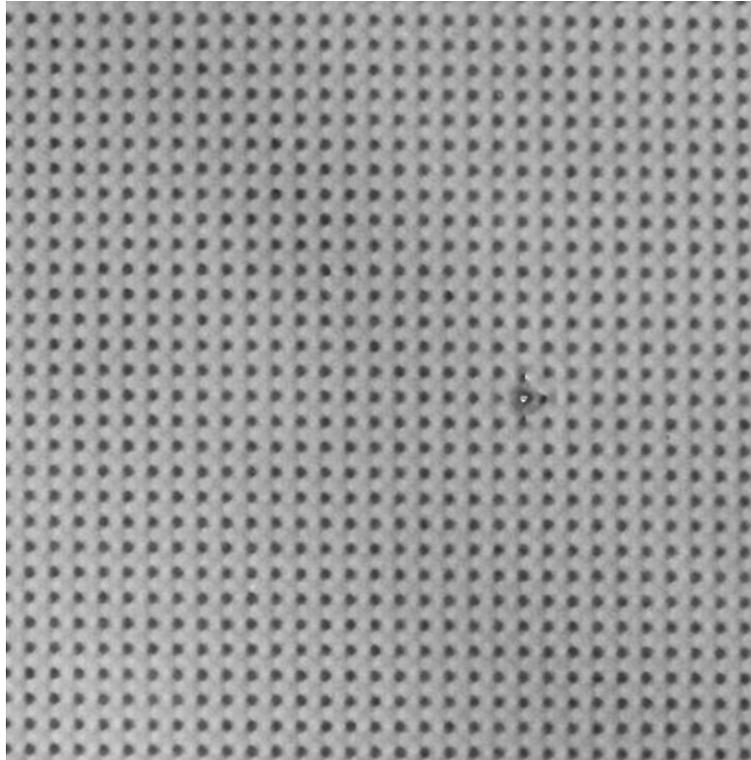

Figure 9: Bad HARI Contact—Aspect Ratio of 6.8:1. Gray-Scale Phase Image of ISMT HARI Wafer showing single bad contact in an array of good contacts. Contacts are 220 nm diameter on a 540 nm pitch with Aspect Ratio of 6.8 to 1, depth divided by diameter. Original hologram made with 266 nm wavelength laser.

4. CONCLUSIONS

The DDH technology shows tremendous promise as an imaging, mapping, and quantitative measurement technology. Initial work on semiconductor wafer defect detection with both the visible tool and the DUV tool are extremely promising, particularly for inspection of high aspect ratio structures. Figure 10 is a picture of the Fathom[TM] Alpha Tool.

Figure 10: Picture of the Fathom Alpha Tool

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