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The metrology of a miniature FT spectrometer MOEMS device using white light scanning interference microscopy

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Abstract

Micro-optical electro-mechanical systems (MOEMS) technology, making use of existing silicon based fabrication techniques shows great potential for making complete miniaturized hybrid devices. Such technology has been used to make a Fourier transform spectrometer based on a time-scanning Michelson interferometer. An electrostatic comb drive actuator moves the scanning mirror over a distance of 40 μm. The measured resolution of the spectrometer is 6 nm at a wavelength of 633 nm. The dimensions of the device are 5×5×0.5 mm, and the depth of feature is 75 μm. During quality control of such devices it is necessary to check the dimensions of micron wide structures that are tens of microns deep, over areas of tens of square millimeters. In this work we have investigated the use of white light scanning interference (WLSI) microscopy for making rapid, non-destructive precision three-dimensional measurements. While a high axial precision can be achieved, an artifact has been observed with classical configurations that tend to extend the location of deep step discontinuities by up to 3 μm and so broaden narrow structures. With certain modifications in the optical configuration, this error can be considerably reduced. The results of this work demonstrate that WLSI shows great potential for the rapid and precise quality control of MOEMS devices.

Keywords: Surface morphology; Silicon; MOEMS; Interference microscopy

1. Introduction

Optical MEMS, or MOEMS (micro-electro-mechanical systems) technology plays an increasingly important role in domains such as telecommunications, optical networking, information storage, wireless technologies, environmental monitoring, and remote sensing and display technology. Components and systems as varied as the optical bench on a chip, integrated optical laser scanners, micro-shutters or optical switches have been developed at an industrial level. The compatibility with integrated circuit technology allows batch processing and production in large quantities at low cost.

The combination of different technologies on the same device brings with it new challenges for carrying out metrology at both research and production levels. New analytical tools are required that are capable of rapidly and non-destructively analyzing inhomogeneous materials, on micron or submicron wide structures that may be tens of microns deep and extend over tens of square millimeters.

White light scanning interferometry (WLSI), or coherence probe microscopy (CPM) is a very promising technique for performing metrology on such complex structures [1,2]. The use of far field imaging and a thin virtual scanning probe plane leads to submicron lateral resolution, nanometric axial resolution and high speed non-destructive analysis of large areas [3–6]. In this work a miniature FT spectrometer made with MOEMS technology [7] has been investigated using WLSI to explore some of the challenges of carrying out fast, accurate three-dimensional metrology on such devices. The spectrometer is based on a scanning Michelson interferometer for use in miniature low cost applications. The system includes narrow (1–2-μm wide) spring structures and closely interleaved electrostatic combs that are 75 μm in height.

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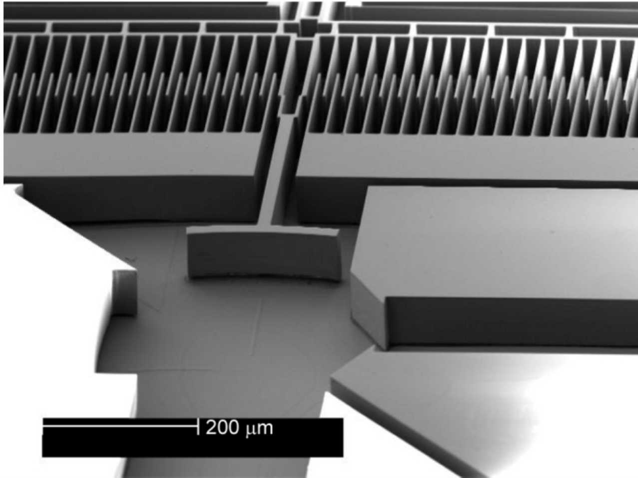

Fig. 1. SEM view of FT spectrometer MOEMS structure (similar to, but not exactly the same as the sample measured in the present work).

Initial three-dimensional measurements using a typical WLSI system with a Mirau interference objective, results in a good overall view with high precision measurement of surface heights. But on closer inspection, an artifact has been detected concerning the exact lateral location of step discontinuities, which can be extended by up to 3 μm. The 1.8–2 μm wide comb teeth can thus appear to be up to 7-μm wide. This is surprising since early work on CPM used for measuring critical dimensions of micron high and wide grating structures demonstrated the possibility of achieving submicron measurement precision (0.010–0.019 μm) in determining edge location using a high resolution Linnik interferometer [8].

Height artifacts known as 'batwings' at the edges of step discontinuities are known to exist for steps lower in height than the coherence length of the light used (typically less than 1 μm) [9,10], described as being due to diffraction effects at the step discontinuity. But this has not been linked to uncertainties in the edge location.

In this work we have therefore investigated the use of different interference objectives with variable aperture diaphragm openings at different wavelengths to try and better understand the problem of lateral artifacts at step discontinuities and to propose an initial solution to reduce the lateral measurement errors when making full three-dimensional measurements of MOEMS structures.

2. Experimental

2.1. Fabrication of the miniature FT spectrometer MOEMS device

Fourier transform spectroscopy is a well-known and widely used technique for the measurement of spectra of weak extended sources, providing a higher signal-to-noise ratio performance compared with other methods. Miniature spectrometers are becoming increasingly attractive for new applications as varied as color measurement, industrial process control, environmental monitoring and medical diagnostics.

The MOEMS device (Fig. 1) [7] is based on a miniaturized Michelson interferometer used in a time-scanning Fourier transform spectroscopy mode. An electrostatic comb drive actuator moves the scanning mirror through a maximum driving distance of 40 μm at a frequency of 1 Hz. The actuator and the mirrors are fabricated in a single etch step by deep reactive ion etching (DRIE) of silicon on insulator (SOI) wafers. The dimensions of the overall device are 5×5×0.5 mm. The measured resolution of the spectrometer is 6 nm at a wavelength of 633 nm.

An important aspect of the metrology of such a MOEMS system is the three-dimensional measurement of the different structures in order to determine the process parameters of the etching technique used and to check the precision that can be achieved.

2.2. WLSI measurement system

Details of the WLSI measuring system can be found in Ref. [2], which is based on two microscopes. The first is a Leitz Linnik microscope with x10 and x50 Linnik objectives (see Table 1 for details), an incandescent lamp and source focus illumination. The second is a Leica DMR-X microscope with x10 and x40 Mirau objectives (Table 1), a halogen lamp with a selection of interference filters available, and Köhler illumination. A Sony XC-75E CCD camera with a standard 8 bit digital imaging board is used for image capture and digitaliza-

Table 1
Variation of comb structure width with interference objective when profiled with CPM in white light (spectral range 400–1000 nm)

Objective	Numerical aperture	Lateral resolution (μm)	Comb structure width (μm)	
			Aperture diaphragm open	Aperture diaphragm closed
x10 Linnik	0.18	2.07	5.26	3.54
x10 Mirau	0.25	1.49	6.88	7.16
x40 Mirau	0.6	0.62	5.34	5.14
x50 Linnik	0.85	0.44	5.1	3.04

tion. The sample is mounted on a piezoelectric transducer (PZT) table with linear feedback (LVDT – linear variable differential transformer) control having a vertical sensitivity of 10 nm over a range of 100 μm.

The algorithms for system control, and image processing was developed in-house. The modulation contrast detection algorithm based on Ref. [11] was used ‘on-the-fly’ to measure the full depth of the structure (75 μm) over an image size of 760×572 pixels. To investigate the XZ images and Z profiles at a given position, a full series of 1000 images 128×128 pixels in size were stored in RAM.

3. Measurement results

3.1. Initial measurements of MOEMS using a standard configuration of WLSI

Initial measurements carried out on the MOEMS device were performed using a standard WLSI configuration consisting of the x10 Mirau objective on the Leica DMR-X microscope, with white light and the aperture diaphragm of the illumination system fully open. As has been well established with this technique [3,4], the heights of the different structures can be measured to a high precision, in this example to within 100 nm over the full 75-μm depth. Higher precision can be obtained using interpolation. On closer inspection of the results, artifacts were found to be present at step discontinuities, resulting in the measured widths of narrower structures being too high and micron wide structures having missing detail.

Finer analysis of step edges showed that the system was extending the measured position by up to 3 μm, resulting in a false location. The profiles of an edge structure in Fig. 2 show the advance of the measured step edge from the height profile (solid line) compared with the real position (dotted line) from the intensity profile of the reflection image. For the sake of comparison, the edge positions are taken at half the height and intensity values, respectively. The same positive error remained even after rotating the sample around the optical axis by 90°, excluding the possibility of a directional system error. Carefully making a full depth Z scan of a comb tooth structure, further analysis of the XZ image revealed the presence of ‘ghost’ fringes extending out into empty space at the top of the step and inwards underneath the bottom of the step (Fig. 3). The artifact in edge location arises from the presence of

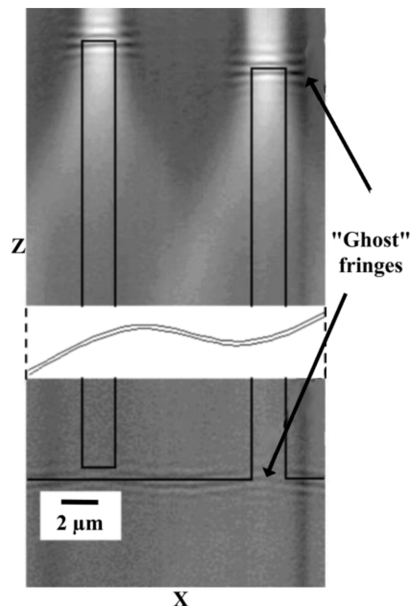

Fig. 3. Contrast enhanced XZ image taken from an XYZ image matrix showing presence of ‘ghost’ fringes appearing near step discontinuities (comb teeth) measured with the x40 Mirau objective with the aperture diaphragm fully open in white light.

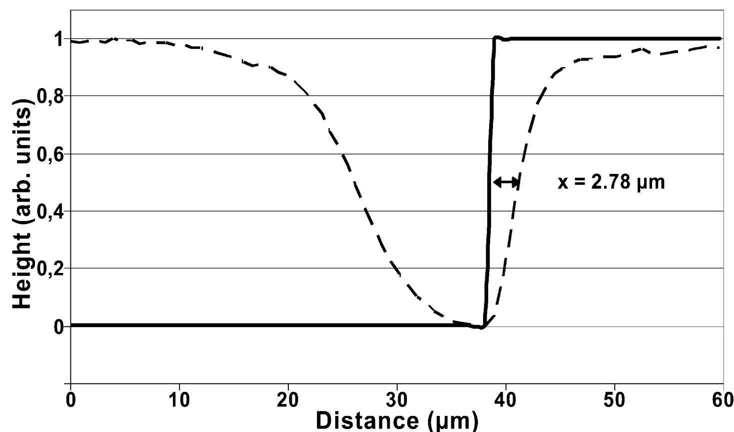

Fig. 2. Advance of measured edge location (solid line) of step discontinuity from FT spectrometer measured with the x10 Mirau objective in white light with the aperture diaphragm open compared with the deep reflection image (dotted line).

the higher contrast ‘ghost’ fringes at the top of the step detected by the algorithm.

3.2. WLSI measurements using different objectives

To better understand the origin of this edge artifact, a series of width measurements of the same comb tooth (known to be 1.8–2-μm wide from SEM images) were made using different interference objectives. The aperture diaphragm was used fully open and then nearly fully closed. In the case of the x40 Mirau objective, different wavelengths were also tested.

The results of the widths measured at the half height positions (Table 1) show that for the Mirau objectives, the values are slightly lower for the larger numerical aperture, but show no improvement when stopping down the aperture diaphragm. For the x40 Mirau objective, there is a slight improvement at shorter wavelengths, giving a width of 5.74 μm in red light ($\lambda = 632$ nm) and 4.26 μm in green light ($\lambda = 450$ nm). In contrast, with the Linnik objectives, there is a dramatic improvement just by stopping down the aperture diaphragm and a further slight improvement with the larger numerical aperture, resulting in a width of 3.04 μm for the x50 Linnik with the aperture diaphragm closed down.

3.3. Optimized WLSI measurements of MOEMS

Having demonstrated the presence of edge artifacts leading to too high measured widths, and studied some of the different optical conditions for reducing these effects, the MOEMS was re-measured using the x10 Linnik objective with the aperture diaphragm stopped down. The results (Fig. 4) show a big improvement, the narrow structures appearing narrower, the edge positions of steps being closer to their true positions and micron wide structures not having the missing points. Using shorter average wavelength light would have improved these results further but this was not possible on the Leitz microscope.

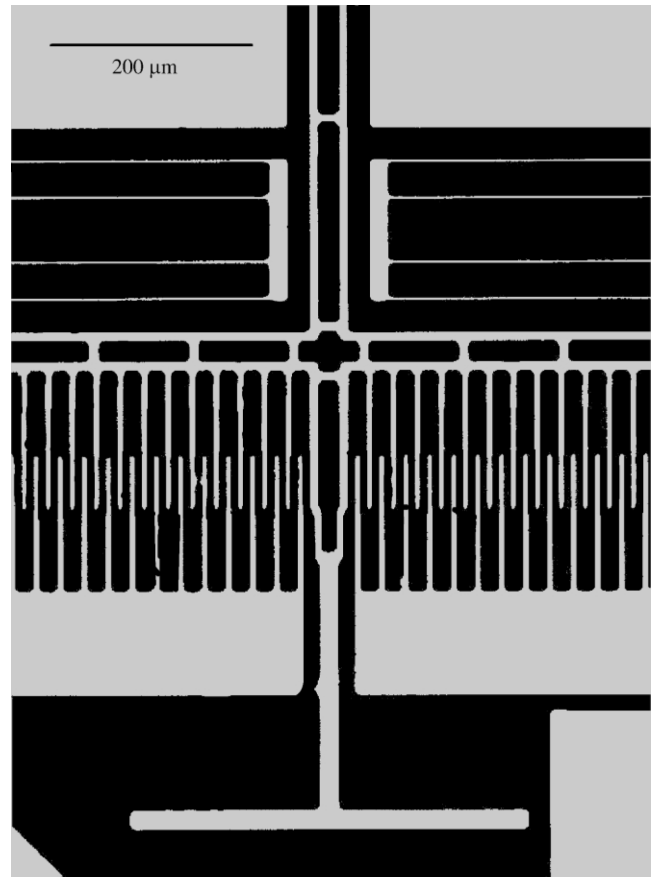

Fig. 4. Improved measurements of MOEMS spectrometer using modified CPM-x10 Linnik objective with aperture diaphragm closed down in white light.

4. Discussion and conclusions

Three-dimensional measurement of a MOEMS FT spectrometer using a standard configuration of WLSI has revealed the presence of an edge artifact, making step edges appear to be up to 3 μm further away from where they really are and narrow structures appearing to be up to 6 μm wide. The origin of this problem appears to be due to the presence of ‘ghost’ fringes near to the edge of step discontinuities, leading to a false detection of the position of the edge.

Analysis of the width of a comb tooth structure with different objectives under different optical conditions has shown that smaller, more accurate widths are measured when using the Linnik objective with the aperture diaphragm closed down, and at shorter wavelengths. The Mirau objectives at longer wavelengths lead to the greatest errors, which cannot be greatly reduced by the optical means employed in this work. The fact that the results are improved when the aperture diaphragm is closed down suggests that the artifact is linked not just to diffraction effects, but also to the use of conical illumination of the samples. Stopping down the aperture diaphragm reduces the angle of the illumination cone, and reduces the artifact. In the case of the Mirau objectives, the ability to reduce the artifact is limited by the fact that the cone angle cannot be reduced greatly due to the presence of the reference mirror along the line of sight [5].

It should be noted that the measurement improvements reported are due solely to modifications in the optical system in the case of standard fringe envelope algorithms and that submicron step location precisions could be achieved using lateral calibration [8].

Further work is being carried out to better understand the origin of this artifact and to further improve the lateral measurement precision of the WLSI system in

the case of three-dimensional measurement of steps and micron wide structures that are tens of microns in height.

Acknowledgments

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