Optics & Laser Technology 92 (2017) 109–119

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Accurate submicron edge detection using the phase change of a nano-scale shifting laser spot

Hoang Hong Hai[a], Liang-Chia Chen[a,b,*], Duc Trung Nguyen[b], Shyh-Tsong Lin[c], Sheng Lih Yeh[d], Ying Yao[b]

[a] Department of Mechatronics, School of Mechanical Engineering, Hanoi University of Science & Technology, No. 1 Dai Co Viet Road, Hanoi, Vietnam
[b] Department of Mechanical Engineering, National Taiwan University, 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan
[c] Graduate Institute of Electro-Optical Engineering, National Taipei University of Technology, 1, Sec. 3, Zhongxiao E. Rd., Taipei 10608, Taiwan
[d] Department of Mechanical Engineering, Lunghwa University of Science and Technology,, No.300, Sec.1, Wanshou Rd., Guishan District, Taoyuan City 33306, Taiwan

ARTICLE INFO

Keywords:
Focus probe
Nanopositioning stage
Super-resolution
Edge detection
Diffraction grating
Step height
Line width

ABSTRACT

Accurate edge detection with lateral super-resolution has been a critical issue in optical measurement because of the barrier imposed by the optical diffraction limit. In this study, a diffraction model that applies scalar diffraction theory of Fresnel–Kirchhoff is developed to simulate phase variance and distribution along edge location. Edge position is detected based on the phase variation that occurs on the edge with a surface step-height jump. To detect accurate edge positioning beyond the optical diffraction limit, a nanopositioning stage is used to scan the super steep edge of a single-edge and multi-edges submicron grating with nano-scale, and its phase distribution is captured. Model simulation is performed to confirm the phase-shifting phenomenon of the edge. A phase-shifting detection algorithm is developed to spatially detect the edge when a finite step scanning with a pitch of several tenth nanometers is used. A 180 nm deviation can occur during detection when the step height of the detecting edge varies, or the detecting laser spot covers more than one edge. Preliminary experimental results show that for the edge detection of the submicron line width of the grating, the standard deviation of the optical phase difference detection measurement is 38 nm. This technique provides a feasible means to achieve optical super-resolution on micro-grating measurement.

1. Introduction

With the design rules and wafer dimensions in the semiconductor or optical data storage manufacturing industry recently reaching 100 nm and 300 mm, respectively, the demand for determining edge position within an accuracy of 10 nm has been increasing [1]. At present, investigations on lateral nano-scale super-resolution show that to accurately determine line width measurement with optical scanning technologies, particularly accurate lateral edge detection is required. However, the minimum measurable line width is restricted by the classical resolution limit of optical systems. The Rayleigh original criterion is used to define the resolution mathematically when the central maximum of one Airy disc lies over the first minimum of the other, in which two measured points that produce Airy discs can just be resolved individually. If we assume that the light source is incoherent and a circulate aperture associated with a microscope objective is employed, the Rayleigh criterion diffraction limit can be expressed as follows [2]:

$$d_{x,y} = \frac{0.61\lambda}{NA}, \tag{1}$$

where λ is the wavelength of the light source, and NA is the numerical aperture of the optical system.

In an optical interferometric system, the batwing effect is a well-known phenomenon that is observed around a step discontinuity especially for the case of a step height that is less than the coherence length of the light source, in which the height difference between two adjacent measurement points smaller than λ/4 could not be accurately solved. It is usually explained as the interference between reflections of waves normally incident on the top and bottom surfaces. When the distorted diffraction image is measured, the edge position for purely topographic line width measurement may fail completely below a certain width because both edge minima will merge into one. To solve this problem, various novel techniques have been compared with atomic force microscopy (AFM), which measures direct contact between the tip and the edge in contact mode or near collisions at the edge in non-contact mode. An exponential fitting algorithm was

* Corresponding author at: Department of Mechanical Engineering, National Taiwan University, 1 Sec. 4, Roosevelt Rd., Taipei, 10617, Taiwan.

http://dx.doi.org/10.1016/j.optlastec.2017.01.006
Received 23 July 2016; Accepted 11 January 2017

developed for edge detection with an expanded uncertainty of ± 2σ less than 15 nm achievable [3]. Another AFM measurement strategy was proposed by PTB, in which the 2D gratings are measured in two narrow rectangular areas for determining all desired measurands [4]. Meanwhile, in scanning electron microscopy (SEM) images, edge detection is often performed by thresholding the spatial information of a top-down image. To increase measurement accuracy, an edge boundary detection technique based on the wavelet framework is proposed to achieve nano-scale edge detection and characterization by providing a systematic threshold determination step [5]. Furthermore, an algorithm based on a self-organizing unsupervised neural network learning is developed to classify pixels on a digitized image and extract the corresponding line parameters [6]. The technique was demonstrated on the specific application of edge detection for linewidth measurement in semiconductor lithography. In comparison with the SEM imaging, the method can achieve an edge detection with a maximum relative discrepancy of 2.5%. Other optical systems have been developed and implemented, thereby leading to the potential establishment of advanced imaging systems with a resolution capability that reaches beyond the diffraction limit of several hundreds to less than 100 nm. These methods are based on either intensity [7–10] or phase detection [11–17]. Yokozeki et al. [18] developed an iterative super-resolution imaging process based on the Richardson–Lucy deconvolution algorithm [19] by using standing wave superposition combined with nanopositioning scanning to detect objects below the diffraction limit. However, when this method is used to detect nanoparticles in 2D applications, it fails when existing noise is higher than a spatial frequency of ~9.5 μm^{-1}, which is equivalent to 105 nm; also, frequency components above the crossover frequency cannot be recovered [20]. Compared with intensity detection, the phase effect has been detected in the edge region since this idea of phase imaging with phase singularities was first explained by Nye et al. [21]. The concept of super-resolution phase defects was introduced by Tychinsky [12,22,23]. A common path interferometric method provides selective edge detection for line structures because polarization difference is localized at structure edges. Zhu and Probst [15,16] proposed using an abrupt nonlinear phase variation in a differential interferometer to detect an edge. In their scheme, a heterodyne differential interferometer was modified to produce two polarization mixing beams. When one beam scans across an edge, an abrupt phase variation close to 180° occurs. If the phase difference between two same-frequency beams is adjusted close to 180°, then a sharp phase variation may occur instead of a phase jump. Furthermore, the position of the largest slope in the phase variation is related exactly to the relative position between the scanned spot and the edge. This phenomenon can be used to determine the edge position with good certainty. Therefore, phase jump can be an ideal index for edge location. Masajada et al. [24] investigated the diffraction effects of focused Gaussian beams that produced a double optical vortex using a nano-step structure fabricated in a transparent medium, which could be improved by a factor of 15. Hence, measuring the phase that provides additional information regarding the microstructure, is useful for reconstructing an object.

In this research, a technique used a high-magnification Mirau interferometer objective lens, combined with a nanopositioning stage, is developed for locating the edge of subwavelength structures. This research aims to achieve the following objectives: (1) to demonstrate the theory of edge location via the phase variation principle based on theoretical diffraction simulation using the Fresnel–Kirchhoff model, (2) to develop an experimental system to verify the theoretical result with the simulation result. The positioning accuracy of the line edge is verified by measuring the grating line width which is defined as a distance between two neighboring line edges of a micro grating.

2. Measurement principle

2.1. Theory of diffraction model

Fig. 1 shows the shape of laser point spot on the grating at different scanning positions. When the light is reflected entirely by the substrate or grating top surface, the inspecting light can be simply modeled by light reflection. However, when the inspecting light spot is partly engaged with the grating structure, it is partly reflected by either the substrate or grating top surface while the grating edge induces light diffraction, so some of light energy is diffracted away from the inspecting beam. The behavior of the inspecting beam being interacting with the grating structure in the scanning process is modeled and investigated by the scalar diffraction analysis as follows.

In this study, the diffraction light amplitude is calculated at a distance that is significantly longer than one wavelength. A scalar diffraction analysis using the Fresnel–Kirchhoff integral to describe Gaussian beam scattering from a phase step surface was conducted by Singher et al. [25]. The diffraction model is described in Fig. 2.

When a Gaussian beam incident is focused on a conducting surface, the complex amplitude of the Gaussian beam in scalar approximation is given under the TEM_{00} mode as follows:

$$E(x,y,z) = E_0\frac{\omega(0)}{\omega(z)}\exp\left\{-r^2\left[\frac{1}{\omega^2(z)}\right]+\frac{jk}{2R(z)}\right\}\times\exp(-jkz)\exp\left[j\tan^{-1}\left(\frac{z}{z_0}\right)\right], \tag{2}$$

where E(x,y,z) is the complex amplitude of the diffracted light at a distance z from the aperture plane to the observation plane, and $E_0(x_0,y_0,z=0)$ is the complex amplitude at the aperture plane. The functions $\omega(z)$ and R(z) are referred to as the beam waist and the curvature radius of the phase font, respectively.

$$\omega^2(z) = \omega^2(0)\left(1+\frac{z^2}{z_0^2}\right), \tag{3}$$

$$R(z) = z+\frac{z_0^2}{z}, \tag{4}$$

$$z_0 = \frac{\pi\omega^2(0)}{\lambda}, \tag{5}$$

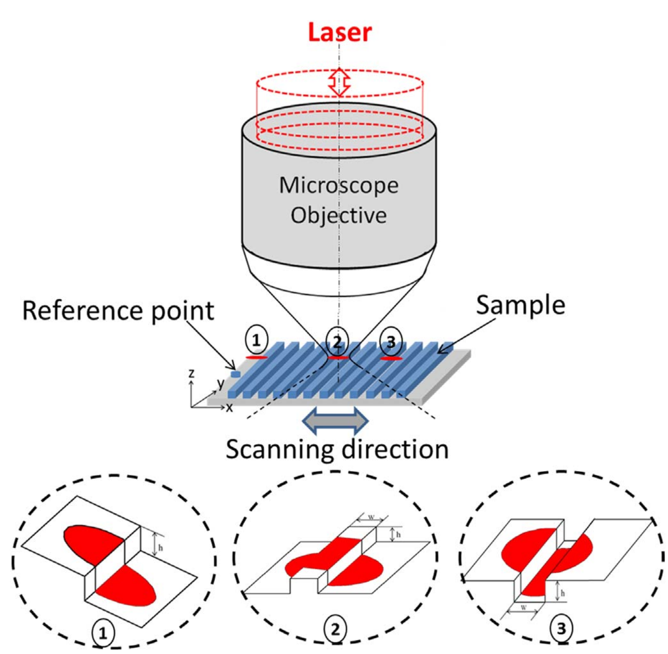

Fig. 1. Schematic diagram of the laser spot scanning at the (1) phase step, (2) single line-width, and (3) groove of the grating sample.