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Image based in situ electron-beam drift detection by silicon photodiodes in scanning-electron microscopy and an electron-beam lithography system

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ABSTRACT

A silicon-photodiode detector can be used to sense the position of the electron beam in a scanning-electron microscope. In order to validate the implementation of a electron beam drift detector, a silicon photodiode was constructed with a low profile and small working distance. The performance in detecting the drift of the electron beam over time was analyzed. It was also shown that a back scattered-electron image can be created with electron scanning, which allows the development of highly sensitive in situ beam position feedback in the electron-beam direct-write lithography system.

1. Introduction

An electron-beam lithography system uses an electron beam as the source, and is not subject to the diffraction limitation present in focusing in optical lithography. This greatly improves the resolution and makes it possible to write photoresist patterns on the wafers without using masks. The next generation of lithography systems might employ multiple parallel direct writing systems [1], which would avoid the insufficient direct-writing throughput of the traditional electron-beam system. The use of a multiple-electron-sensor array would enable the position of each electron to be monitored and the drift of the electron beams to be detected, which is due to electron charges in the system and the thermal effect in the process of the electron-beam exposure during long-time operation interfering with the electron beams and the electron fields of the electromagnetic lens. The beam drift reduces the resolution and accuracy in the alignment of electron beams.

Therefore, if the electron beams cannot be calibrated frequently it is impossible to achieve high throughputs and yields. In an early attempt, Ogasawara et al. [2] used a semi-blocked Faraday cup (1995) to detect the beam drift by detecting if the e-beam current was earthed. Later, Ando et al. [3] investigated the beam drift by observing the contamination layers on a second shaping aperture. This effort was an off-line process. Goodberlet et al. [4] started to detect the drift of electron beams using interferometer platforms, but this approach cannot detect the drift of each electron beam in a multiple-electron-beam system. For real-time beam position control, Hastings et al. [5] devised a fiducial grid on the substrate to achieve online e-beam positioning signal feedback. This approach would require very expensive preprocessing.

A silicon photodiode [6] can be used to detect back scattered electrons in a single-electron-beam system. The properties of high gain, small sensitive area, and rapid response of such a photodiode mean that it has potential as a secondary-electron detector [7]. The small-diameter central hole provides a high electron collection capacity because most of the back scattered electrons are close to this hole. Moreover, the silicon photodiode can be easily integrated into an electron-beam lithography system without requiring a large operating voltage (less than 50 V), preventing stray effects on the paths of the electron beams. The silicon photodiode has the potential to replace other secondary-electron detectors such as MCP and E–T detectors [8].

This paper explores the use of the photodiode for e-beam position/drift detection. The back scattered electrons are highly dependent to the incident beam. Using a quadrature detector to detect the deflection of the back scattered beam provide a measure to the incident beam location [9]. This approach, however, gives very low signal to noise ratio. Even with all the efforts of time domain data regression one still cannot surpass resolutions that are in the micrometer range. This is a resolution too low to meet the need for current day electron beam lithography. To achieve the required resolution, this paper proposes to use the image processing technique. Although the time domain signal is very noisy, the bulk image from the space domain is very consistent and is high sensitive to the location of the beam. With the advancement of multiple

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e-beam system, it is possible to dedicate some of the e-beam sources for positioning. Notice that the concern is on the beam drift which is a macro property of the source relative to the target. The characteristics of a few typical beams will be able to describe the behavior of the neighboring areas. We have implemented the concept on a SEM e-beam writer. The experimental results show that the analyses yield results with sub-nanometer resolution.

2. Electron-beam imaging for beam drift detection

This paper explores the use of the photodiode for e-beam position detection. The back scattered electrons are very sensitive to the position of the incident beam. Using the photodiode to detect the distribution of the back scattered electrons can be used as a sensitive measure of the electron beam position.

Traditional Moiré patterning for IC wafer alignment achieves sub-micrometer accuracy which is insufficient for direct write e-beam lithography applications. Typically, one desires at least nanometer resolution for achieving lithography half pitch in the range of ten nanometers. An intuitive approach was to use a quadrature detector to measure the distribution of the back scattered electrons. This distribution caused imbalance in the detector currents and thus gave the electron beam deflection. And as described in the introduction, the back scattered electron signal was very noisy and yielded very poor measurement results. The resolution was in tens of micrometer range. Our attempts to deduce statistical properties from the time sequence had limited effect due to the inherent random shifting characteristic of the rebounding electrons and the drifting property of the beam. During our study, we noticed that the instantaneous electron image obtained from the back scattered electron is itself consistent with very rich positioning information. It would be possible to deduce position information from the electron image. Furthermore, this measurement on the relative position between the electron source and the substrate is the crucial information for the e-beam lithography process and can be used for direct servo feedback. All other positioning measurements such as the laser interferometry are non-collocated and require extreme precision and servo rigidity to achieve the same accuracy. This section then explains the procedures to derive the positioning information from the back scattering electron images.

2.1. Drift detection

Beam drift can be detected by comparing the frames in a series of scanning-electron images using a convenient positioning mark, in this case a preprocessed silicon tip as shown in Fig. 1. The silicon tip had a pyramidal shape, as shown in the secondary electron images in Fig. 2. Before drift measurements, the sample with photoresist patterns was placed in the vacuum chuck for at least 5 hours so as to eliminate thermal interactions between the sample and chuck. For the drift measurement study, an image was obtained every 2.5 min for the duration of 1 h.

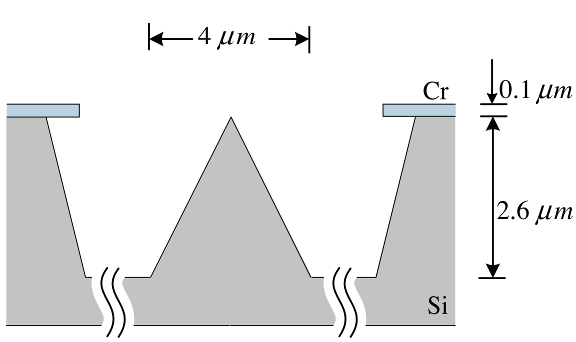

Fig. 1. Profile of the silicon tip.

2.2. Image-procession algorithm

The image processing procedure follows the phase correlation approach [10] in which two images taken from the same position at different time instances are compared and the difference between the two frames was measured directly from their phases. First, the 2-D Fourier transform was applied to two frames:

$$\begin{aligned} G_a &= F\{g_a\} \\ G_b &= F\{g_b\} \end{aligned} \tag{1}$$

The cross-power spectrum was then calculated by taking the complex conjugate of the second result, and normalizing this product as follows:

$$\Phi = \frac{G_a G_b^*}{|G_a G_b^*|} \tag{2}$$

Finally, the inverse Fourier transform applied to seek the peak point corresponding to the difference in the spatial domain:

$$\begin{aligned} \phi &= F^{-1}[\Phi] \\ (\Delta x, \Delta y) &= \max_{x,y}\{\phi\} \end{aligned} \tag{3}$$

Fig. 3(a) and 1(b) show two sets of e-beam images of a preprocessed positioning reference mark on the substrate. This leads to the beam drift from the detection of the reference mark notable of the sample, while assumed being stationary. The offset between the images computed are then shown in Fig. 4. But beam drift and the difference between the two frames are in the opposite direction as shown in Fig. 4. For the x15000 magnification, there are 1280 horizontal pixels, the corresponding distance of 7935 nm, so a pixel is equivalent to 6.199 nm.

2.3. Responsivity

For characterizing the magnification of the photodiode, we define the responsivity of a silicon photodiode as:

$$R = \frac{I_{ph}}{I_o(E/e)} \tag{4}$$

where I_{ph} is the measured photodiode current, I_o is the incident electron-beam current, E is the electron landing energy, and e is the unit charge of the electron.

3. Experiment setup

This section describes the measurement setup for the study.

3.1. Detector configuration

A silicon photodiode is placed in a scanning-electron microscope (SEM). Four pico-ammeters were used to detect the quadrant currents. The central hole of the silicon photodiode had a diameter of 0.5 mm. The each quadrant sensing area was 11mm2. The responsivity, beam drift, and electron image could be obtained by computation. The entire system based on the silicon photodiode is shown in Fig. 5. A screen with a −60 V bias voltage was positioned directly in front of the silicon photodiode, as shown in Fig. 6(a). Notice that a negative bias was applied on the screen. Instead of the common use of positively biased screen to help trapping more secondary electrons for enhancing the images, we have used a negatively biased screen to filter out the secondary electrons. This was done in an effort to improve the positioning