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Linearity estimation of high accurate energy detector for excimer laser

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ABSTRACT

High accurate pulse energy detection for excimer laser is one of the most important technologies in deep ultra violet (DUV) lithography machine for precise dose control. In order to estimate the linearity of the SIOM proprietary energy detector (ED), a modified correlation method and the corresponding system have been developed. In the proposed method, an identical home-made ED was used as reference in the experimental system showing benefit as pulse energy fluctuation elimination. Secondly, this method provides a solution of high accurate measurement with a reference detector which is the same as the tested detector. The linearity estimation system contains an excimer laser, a beam expander, an adjustable diaphragm, a beam splitter, a reference ED (R-ED), a set of attenuators and a tested ED (T-ED). Experimental results show that, with linear least-squares fitting, the measured nonlinearity factor of the ED is 0.617% in a dynamic range of about 1–10 nJ per pulse, and the combined uncertainty is 1.140%. It is proved that the SIOM proprietary ED can be used in high accurate pulse energy measurement of excimer lasers.

1. Introduction

In the semiconductor industry, silicon integrated circuits have become more and more compact and powerful during the last two decades. Increasing numerical aperture, reducing wavelength or implementing resolution enhancement techniques [1] can be used to improve the resolution of optical projection imaging for lithography tools. Generally, reducing wavelength is preferred for the ease of resolving fine structures [2]. Therefore, the radiation source for lithographic apparatus has been developed from mercury UV lamps to excimer lasers with shorter wavelength under 200 nm. In the lithography machine, it is important to control the exposure dose delivered to the wafer. An incorrect dose leads to variation of line width and other imaging errors. To meet the stringent requirements on critical dimension (CD) uniformity, accurate measurement and active control of exposure dose during exposing wafers is crucial [3]. In the ideal situation, the dose is measured and controlled at wafer level [4]. But it is impossible to expose a die and measure the dose at the same time with a spot sensor (SS), which is positioned in the waferstage. For this reason an energy detector (ED), which is located in the top module of the illumination system, is used to measure and control the energy of the individual laser pulse. This is particularly significant when an excimer laser servers as the radiation source. Before the ED is used to measure and control the pulse energy, its opto-electronic responsibility should be quantitatively determined. One of the most important responsibilities is its linearity.

2. Nonlinearity definition and estimating methods

A detector is defined to be linear when the responsibility is constant and any change of responsibility versus incident power is defined as nonlinearity. In general, the conversion function of a detector can be represented by polynomial

$$E = f(v) = \sum_{i=0}^{n} a_i V^i, \tag{1}$$

where E is the incident laser energy, V is the corresponding voltage signal of the detector and a_i is the coefficient of the conversion function $f(V)$. In practical cases, if the number of the measured data set is larger than that of the unknown coefficients a_i described in Eq. (1), the best-fit polynomial function for $f(V)$ can be calculated with the assumption that the sum of the squared residuals is minimum. When a_i $(i > 1)$ is equal to zero, the best-fit polynomial function becomes a linear fitting.

Nonlinearity factor is the maximum deviation of a sensor's input–output characteristic curve from the end point linearity or best-fit or least squares best-fit line and is expressed as a

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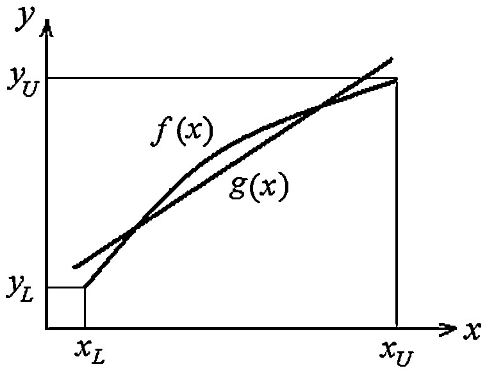

Fig. 1. Rationale for the definition of the nonlinearity factor. $f(x)$ is the actual response curve within a domain bounded by y_L and y_U, and $g(x)$ is a linear fitting with the least-squares method.

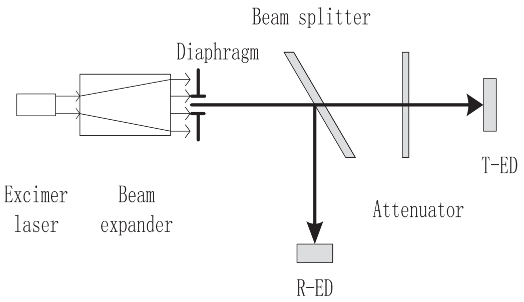

Fig. 2. Schematic representation of the linearity estimation system. The radiation source is a 193 nm ArF excimer laser. The beam splitter has a splitting ratio of about 5:1. Most of the pulse energy is received by the T-ED so that the system has an enough dynamic range while the R-ED showing a good SNR as well. The attenuator is used to attenuate pulse energy received by the T-ED. The T-ED and the R-ED are identical and their outputs are read synchronously.

percentage of full-rated output. The nonlinearity factor described in this letter is defined as

$$\xi_{ls} = \frac{|f(x_i) - g(x_i)|_{\max}}{y_U - y_L} \times 100\% \qquad (2)$$

As shown in Fig. 1, $f(x)$ is the actual response curve within a domain bounded by y_L and y_U, and $g(x)$ is a linear fitting with the least-squares method.

There are many methods for estimating the linearity of a detector's response. The superposition method, which requires a very stable laser source, is usually used to measure the linearity of optical fiber power meters [5,6]. It is difficult to characterize excimer laser pulse energy detectors because the energy output of excimer laser fluctuates from pulse to pulse due to warm-up, gas fill degradation or rejuvenation [7].

In the attenuation method, an attenuator, such as an optical filter or an adjustable diaphragm, of known transmission is used to vary the laser pulse energy [8,9]. The unstable outputs of excimer lasers also make it impractical to implement this method for detector linearity determination.

In the correlation method, the output of the detector under test is compared with a monitor detector [9,10]. This method can reduce excimer laser pulse fluctuations because the output of the detector under test and that of the monitor detector are read simultaneously. However, the monitor detector is different from the detector under test, so their opto-electronic responsibilities are not the same and the above method cannot remove pulse fluctuation ultimately. Additionally, the monitor detector is assumed to be linear in the correlation method and it must be tested against several other detectors including a primary standard calorimeter to determinate its linearity; this process is complex and time-consuming. In order to solve these problems, we have put forward a modified correlation method and developed the corresponding system.

3. The modified correlation method and the corresponding system

In the modified correlation method, the tested ED (T-ED) and the reference ED (R-ED) are identical and their opto-electronic responses are theoretically same as each other. In addition, the T-ED and the R-ED are used to detect beam in two light arms synchronously by using a beam splitting element. Therefore, the ratio of the T-ED output to the R-ED output dubbed the relative T-ED output is theoretically independent of excimer laser pulse energy fluctuations, which serves as the measurement principle of this method.

The schematic diagram of the linearity estimation system on the basis of the modified correlation method is depicted in Fig. 2. The system contains an excimer laser, a beam expander, an adjustable diaphragm, a beam splitter, an R-ED, a set of attenuators and a T-ED. The laser is a 193 nm ArF excimer laser (GAM-EX5-500, pulse width 8–16 ns, maximum pulse energy ~5 mJ, polarization degree of 95% at least and repetition rate up to 500 Hz). The incident beam is expanded by the beam expander and the center part of the expanded beam is selected by the adjustable diaphragm so as to reduce spatial fluctuations of the incident laser beam. Then, the beam from the diaphragm is split into two beam-lets by the beam splitter. In the transmission path, the beam reaches the T-ED via a set of attenuators whose transmittance change in a dynamic range of about 10–100%. The other beam is received by the R-ED in the reflection path.

In our experiment, splitting ratio of the beam splitter is about 5:1 (the ratio of the transmitted beam to the reflected beam). Most of the pulse energy is received by the T-ED so that the system has an enough dynamic range. Meanwhile, the SNR of the R-ED output is no less than 48 dB. The influence of the R-ED can be cut down further with nine-point moving average so that the influence of the R-ED is negligible.

Moreover, in order to estimate the impact of the polarization degree, splitting ratios of the beam splitter with different incident beam polarization degree are simulated by LightTools. As shown in Table 1, the relative deviation of the splitting ratio is less than 0.25% when the polarization degree of the incident beam is more than 95%. Similarly, the influence of the incident beam polarization on measurement results can be cut down further by digital filtering so that it is negligible too.

The T-ED linearity was measured through these processes in following. Fire the laser with 50 Hz repetition rate. Adjust the diaphragm until the T-ED output was set at the maximum without any attenuation in the transmission path. The laser of the transmission path was measured by an energy meter (Ophir PD10-C) and that of the reflection path was measured by the R-ED so as to obtain the ratio of the energy meter to the R-ED. Then, the output of the T-ED and R-ED were read out synchronously. Further, an attenuator of known transmission was inserted into the transmission path to cause a ~10% pulse energy decrease and record the measured data pairs again. Repeat the above step until the low end of the meter range was reached. Finally, a linear function was fitted by least-squares method and the T-ED nonlinearity factor was calculated with Eq. (2). Due to the pulse fluctuation of the 193 nm ArF excimer laser, the measured data exhibit large noise. In order to lessen the effect of the noise, 50 laser pulses were acquired at one calibrated point. Additionally, a proper time delay before data