Front. Optoelectron. China 2008, 1(1–2): 123–129
DOI 10.1007/s12200-008-0015-3

RESEARCH ARTICLE

A real-time exposure dose control algorithm for DUV excimer lasers

Shiyuan LIU (✉), Xiaojian WU, Xinyi QIN

State Key Laboratory of Digital Manufacturing Equipment and Technology, Wuhan National Laboratory for Optoelectronics,
Huazhong University of Science and Technology, Wuhan 430074, China

Abstract A real-time exposure dose control algorithm for deep ultraviolet (DUV) excimer lasers in a step-and-scan optical lithography is presented. By establishing an abstract scan exposure model and analyzing the pulse-to-pulse energy fluctuation characteristics of DUV excimer lasers, a real-time dose regulation is implemented based on closed-loop feedback control, which especially focuses on reducing the effect of pulse energy overshot and pulse-to-pulse stochastic fluctuation. The experiment conducted on an ArF excimer laser with wavelength of 193 nm, repetition rate of 4 kHz, and pulse energy of 5 mJ confirms that such a real-time dose control algorithm is able to achieve a dose accuracy of above 0.89% even with only 20 pulses. It is fully expected that this algorithm will not only meet increasingly stringent dose accuracy requirements for sub-half-micron lithography, but also be helpful to improve lithography throughput as well as efficiency.

Keywords applied optics, deep ultraviolet (DUV) excimer laser, dose control, scan exposure, lithography, energy overshot, pulse energy stochastic fluctuation

1 Introduction

Exposure dose is one of the most critical characteristics of a lithography tool [1] that refers to a special wavelength optical energy which is received per area of a photoresist on the wafer during scan exposure. In mathematics, exposure dose is expressed as the integral of the instantaneous light intensity within an exposure period of time:

$$D = \int_0^T I(t)\mathrm{d}t, \tag{1}$$

where D is exposure dose, T is exposure period of time, and I is instantaneous light intensity varying with time t.

Exposure dose has a direct relationship with the performance of lithography tools such as critical dimension (CD), uniformity of CD and throughput. Thus, it should be under strict control to achieve the best exposure uniformity and stability [2–4].

With lithography tools developed from steppers to scanners, deep ultraviolet (DUV) excimer lasers with wavelength of 248 and 193 nm are popularly used as the exposure light source [5, 6]. Due to pre-heating, gas recession or refreshing, and long-time operation, pulse-to-pulse energy fluctuation and mean energy floating are essential in DUV excimer lasers, and a phenomenon called energy overshot always occurs as well. Energy overshot refers to the higher pulse energy for the first couple of pulses in a burst with an excess of up to 20% over the mean amplitude [7, 8]. A burst consists of a number of pulses, with the delay between pulses determined by the repetition rate. In the process of scan exposure, the die goes through an illuminated slit at a constant velocity to get a number of pulses or a burst of energy. Consequently, the exposure dose is the accumulated energy of all pulses in the burst [9]. Apparently, pulse-to-pulse energy fluctuation, especially energy overshot, influences dose accuracy and dose uniformity significantly, although several pulses may smooth this effect – the more pulses in a burst, the better the smoothness that can be achieved in theory. However, in practical lithography, increasing the number of pulses in a burst is accomplished by adjusting the angle of a variable attenuator, which usually leads to a lower throughput of the scanner and a higher consumption of excimer laser pulses.

Translated from *Acta Optica Sinica*, 2006, 26(6): 878–884 [译自: 光学学报]

E-mail: shyliu@mail.hust.edu.cn

Both pulse-to-pulse energy fluctuation and energy overshot have the intrinsic characteristics of DUV excimer lasers, and their negative effect on dose accuracy and dose uniformity is difficult to eliminate only by improving the performance of the laser, especially by the optical performance. Thus, a proper control strategy is critical as compensation. This paper presents a real-time dose control algorithm to strictly regulate the energy of each pulse with a closed-loop feedback control strategy. By using this algorithm, the effect of pulse-to-pulse energy fluctuation, especially energy overshot, is significantly reduced, and the number of pulses in a burst is used as less as possible. The algorithm is demonstrated to meet increasingly stringent dose accuracy requirements as well as to improve lithography throughput and excimer laser efficiency.

2 Real-time dose control algorithms

2.1 Model of scan exposure

The scan exposure model in step-and-scan lithography is shown in Fig. 1. Each pulse of the light beam emitted from the excimer laser goes through the optical system and finally images on the wafer. To make a scan exposure, the wafer stage and reticle stages have to move the length of the exposure field plus the width of the illuminated slit. This is called scan length. The reticle needs to be scanned in and out of the illuminated slit at a constant velocity to provide a uniform dose over the exposure field because every point in the exposure field needs to be exposed by the whole slit to receive the same number of laser pulses. The movement of the wafer needs to be strictly synchronized with that of the reticle.

During scan exposure, both the repetition rate f of the excimer laser and the effective slit width L are constant, and the wafer stage moves at a constant velocity v, so each point in the exposure field goes through the slit and receives the same number of laser pulses N, which is expressed as

$$N = fL/v. \tag{2}$$

The exposure dose of the ith point in the exposure field, D_i, is the total energy obtained by that point during its travel through the slit

$$D_i = \frac{\eta}{A}\sum_{k=1}^{N} E(k), \tag{3}$$

where N is number of pulses, η is light transmission efficiency of the optical system, A is effective slit area, and $E(k)$ is light energy of the kth laser pulse.

The quality of exposure dose can be evaluated by relative dose accuracy σ as

$$\sigma = \frac{\max|D_i - D_\mathrm{r}|}{D_\mathrm{r}} \times 100\%, \tag{4}$$

where D_r is the required dose, D_i is the actual dose of the ith point, and max means to get the maximum. When the imaging resolution of a lithography tool is 100 nm, the relative dose accuracy should be better than 1%.

2.2 Architecture of dose controller

The architecture of the dose control system in step-and-scan lithography is shown in Fig. 2. The laser light emitted from the excimer laser travels via the underside illumination optical system (including beam expansion lens, position-orientation lens, zoom-axicon lens, etc.) and the variable attenuator to the energy transducer. The laser light then goes through the upside illumination optical system (including energy uniformity rod, scan slit, illuminating lens, et al.), the reticle and the projection lens, and finally produces images onto the wafer. The energy transducer in the optical system can measure the energy of every pulse and is used to calculate the expected energy of the next pulse by a feedback algorithm. With a

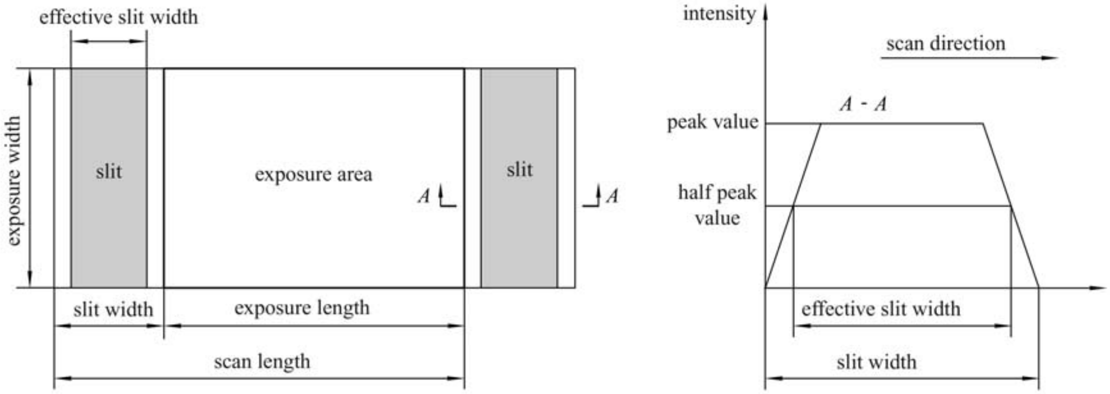

Fig. 1 A scan exposure model for step-and-scan lithography

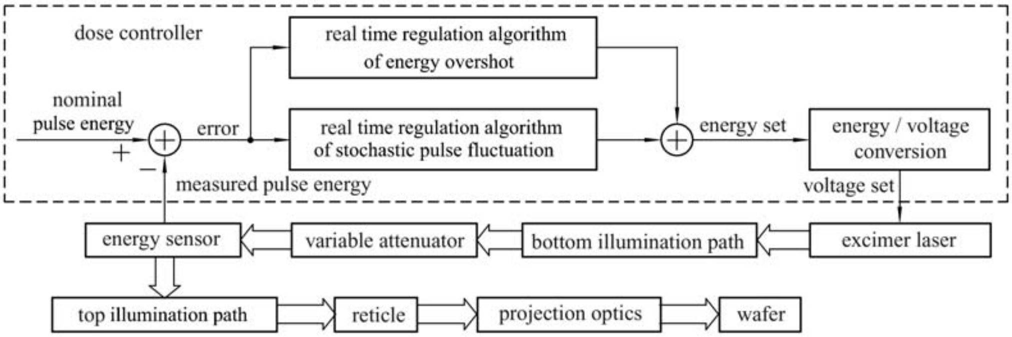

Fig. 2 A dose controller architecture for step-and-scan lithography

predetermined energy-to-voltage conversion function, the actual voltage set point for each laser pulse can be finally obtained and used to control the pulse energy of the laser and guarantee dose accuracy.

The dose controller architecture is shown in the dotted area in Fig. 2. The energy-to-voltage conversion function is achieved through a calibration process. There are usually three kinds of specifications for laser pulse energy: maximum pulse energy, minimum pulse energy, and nominal pulse energy. When performing calibration, the laser is commanded to emit a certain number of pulses with these three values of energy respectively, and the corresponding voltage values are obtained at the same time. Assuming that the relationship between the voltage and the energy is linear, an energy-to-voltage conversion function is evaluated by interpolation. After laser calibration, given a pulse energy E, its corresponding voltage V will be

$$V = V_\mathrm{N} + [E - E_\mathrm{N}]\frac{\Delta V}{\Delta E}, \tag{5}$$

$$\Delta E = E_\mathrm{max} - E_\mathrm{min}, \tag{6}$$

$$\Delta V = V_\mathrm{max} - V_\mathrm{min}, \tag{7}$$

where E_N, E_max and E_min are nominal, maximum, and minimum measured pulse energy, respectively; V_N, V_max and V_min are the corresponding nominal, maximum, and minimum measured voltage, respectively.

2.3 Pulse-to-pulse energy real-time control algorithm

As shown in Fig. 2, a real-time dose control algorithm contains two kinds of regulation algorithms designed to reduce the effect of stochastic pulse fluctuation and energy overshot. The real-time regulation algorithm of stochastic pulse fluctuation is aimed at reducing the effect of pulse-to-pulse energy variation. The calculation of a new energy set point is based on the measured values from previous pulses, or more precisely, based on the moving average of the measured values from previous pulses, thus reducing random pulse-to-pulse variation. The number of previous pulses is no more than the number of pulses N needed by each point in the exposure field when it goes through the slit. The difference between the moving average value and the nominal value determines the energy set point error for the next pulse.

$$\Delta E_\mathrm{s}(1) = 0, \text{ for the first pulse,} \tag{8}$$

$$\Delta E_\mathrm{s}(i) = -k_\mathrm{s}\sum_{f=1}^{i-1}\left[\frac{E_\mathrm{m}(f)}{\varepsilon} - E_\mathrm{N}\right], \text{ for } 2 \leqslant i \leqslant N, \tag{9}$$

$$\Delta E_\mathrm{s}(i) = -k_\mathrm{s}\sum_{f=i-N+1}^{i-1}\left[\frac{E_\mathrm{m}(f)}{\varepsilon} - E_\mathrm{N}\right], \text{ for } i > N, \tag{10}$$

where $\Delta E_\mathrm{s}(i)$ is the energy set point error for the ith pulse considering the stochastic fluctuation, k_s is the regulation coefficient for stochastic fluctuation, $E_\mathrm{m}(f)$ is the measured energy of the fth pulse by the energy transducer, ε is a coefficient converting the measured energy on the energy transducer level into the actual energy on the excimer laser level, and N is the number of laser pulses needed by each point in the exposure field when it passes through the slit.

The real-time regulation algorithm of energy overshot is aimed at reducing the effect of overshot for the first couple of pulses in a burst. Comparatively speaking, energy overshot is a local behavior and can thus be regulated by weighted moving average.

$$\delta E_\mathrm{s}(1) = 0, \text{ for the first pulse,} \tag{11}$$

$$\delta E_\mathrm{s}(i) = -k_\mathrm{o}\frac{1}{i-1}\sum_{g=1}^{i-1}\left[\frac{E_\mathrm{m}(g)}{\varepsilon} - E_\mathrm{s}(g)\right], \quad \text{for } M \neq 1 \text{ and } 2 \leqslant i \leqslant M, \tag{12}$$

$$\delta E_\mathrm{s}(i) = -k_\mathrm{o}\frac{1}{M}\sum_{g=i-M}^{i-1}\left[\frac{E_\mathrm{m}(g)}{\varepsilon} - E_\mathrm{s}(g)\right], \quad \text{for } i > M, \tag{13}$$

where $\delta E_s(i)$ is the energy set point error for the ith pulse considering the energy overshot, k_o is the regulation coefficient for energy overshot, $E_s(g)$ is the calculated energy set point of the gth pulse, and M is the number of moving averages for energy overshot (usually assumed to be 5).

Combining the two algorithms derived above leads to the whole real-time dose control algorithm, which can calculate the energy set point $E_s(i)$ and then the voltage set point $V_s(i)$ for each laser pulse in a burst.

$$E_s(1)=E_N, \text{ for the first pulse}, \tag{14}$$

$$E_s(i)=E_N-k_s\sum_{f=1}^{i-1}\left[\frac{E_m(f)}{\varepsilon}-E_N\right]-k_o\frac{1}{i-1}\sum_{g=1}^{i-1}\left[\frac{E_m(g)}{\varepsilon}-E_s(g)\right], \quad \text{for} \quad M\neq 1 \quad \text{and} \quad 2\leqslant i\leqslant M, \tag{15}$$

$$E_s(i)=E_N-k_s\sum_{f=1}^{i-1}\left[\frac{E_m(f)}{\varepsilon}-E_N\right]-k_o\frac{1}{M}\sum_{g=i-M}^{i-1}\left[\frac{E_m(g)}{\varepsilon}-E_s(g)\right], \quad \text{for} \quad i>M \quad \text{and} \quad i\leqslant N, \tag{16}$$

$$E_s(i)=E_N-k_s\sum_{f=i-N+1}^{i-1}\left[\frac{E_m(f)}{\varepsilon}-E_N\right]-k_o\frac{1}{M}\sum_{g=i-M}^{i-1}\left[\frac{E_m(g)}{\varepsilon}-E_s(g)\right], \quad \text{for} \quad i>N, \tag{17}$$

$$V_s(i)=V_N+[E_s(i)-E_N]\frac{\Delta V}{\Delta E}. \tag{18}$$

3 Experimental results and analysis

To investigate the characteristics of pulse-to-pulse energy fluctuation and energy overshot and to validate the proposed real-time dose control algorithm, the experiment was conducted on an ArF excimer laser with a wavelength of 193 nm, maximum repetition rate of 4 kHz, nominal pulse energy of 5 mJ, and power of 20 W.

Figure 3 shows the actual pulse-to-pulse energy fluctuation measured on the ArF excimer laser, which was operated at a constant high voltage (HV) of 1690 V and a repetition rate of 4 kHz. Figure 3(a) simulates the step-and-scan process of a lithography tool, in which each wafer has 70 exposure fields (20 of them are shown in Fig. 3(a)), each exposure field needs a burst of 375 laser pulses, and the interval between two exposure fields is 100 ms ("+" is used to denote the interval in Fig. 3(a)). In other words, the scan time for each exposure field is 93.75 ms and the step time is 100 ms. Fig. 3(b) depicts the detail of a single exposure field.

It is obvious that the pulse-to-pulse energy of the excimer laser varies significantly and can be demonstrated in two aspects: energy overshot and stochastic fluctuation. The energy overshot happens in each exposure field, since there is an interval of 100 ms between exposure fields. During this interval the excimer laser is in a non-discharge status, and the laser gets more discharged fresh gas when emitting laser pulses again for the next exposure field. Thus, the higher pulse energy is achieved for the first couple of pulses in each exposure even with the same high voltage set point. The laser finally goes into a stable discharge status, and the pulse energy approaches its nominal value. However, the pulse energy always fluctuates around its nominal value due to many uncertain factors.

Figure 4 shows the measured exposure dose of a single scan exposure in constant HV mode. The required dose shown in Figs. 4(a) to 4(f) are 5, 10, 20, 30, 40, and 50 mJ/cm^2, respectively, and the corresponding number of pulses in the slit are 10, 20, 40, 60, 80, and 100, respectively. When operational conditions such as scan velocity, repetition rate, and nominal pulse energy remain unchanged, it is clear that the exposure dose is the energy accumulation of several pulses which smoothes the effect of pulse-to-pulse stochastic fluctuation. The more pulses, the better the smoothing effect achieved.

The step-and-scan exposure experiment for many exposure fields under different dose requirements in a constant HV mode was carried out and the statistical results of measured exposure dose are shown in Table 1, where D_r is the required dose, $D_{\max}$ and $D_{\min}$ are the measured maximum and minimum dose, respectively, and σ is the dose accuracy calculated by Eq. (4). As shown clearly, although energy accumulation over a number of pulses can smooth the pulse-to-pulse stochastic fluctuation significantly, this smoothing tends to be no more efficient as the number of pulses reaches a certain value. Furthermore, the achieved dose accuracy is too poor in constant HV mode due to the existence of energy overshot. The dose accuracy is just 11.9% even with a number of pulses of 100, which obviously cannot meet the dose requirements for microlithography and thus requires an improved real-time dose control algorithm.

Figure 5 depicts the measured pulse energy fluctuation using the real-time dose control algorithm proposed above, with the excimer laser at external high voltage mode, i.e., the high voltage set point of each laser pulse is calculated by the algorithm. The other experimental parameters are just the same as those in Fig. 3. Figure 5(a) simulates the

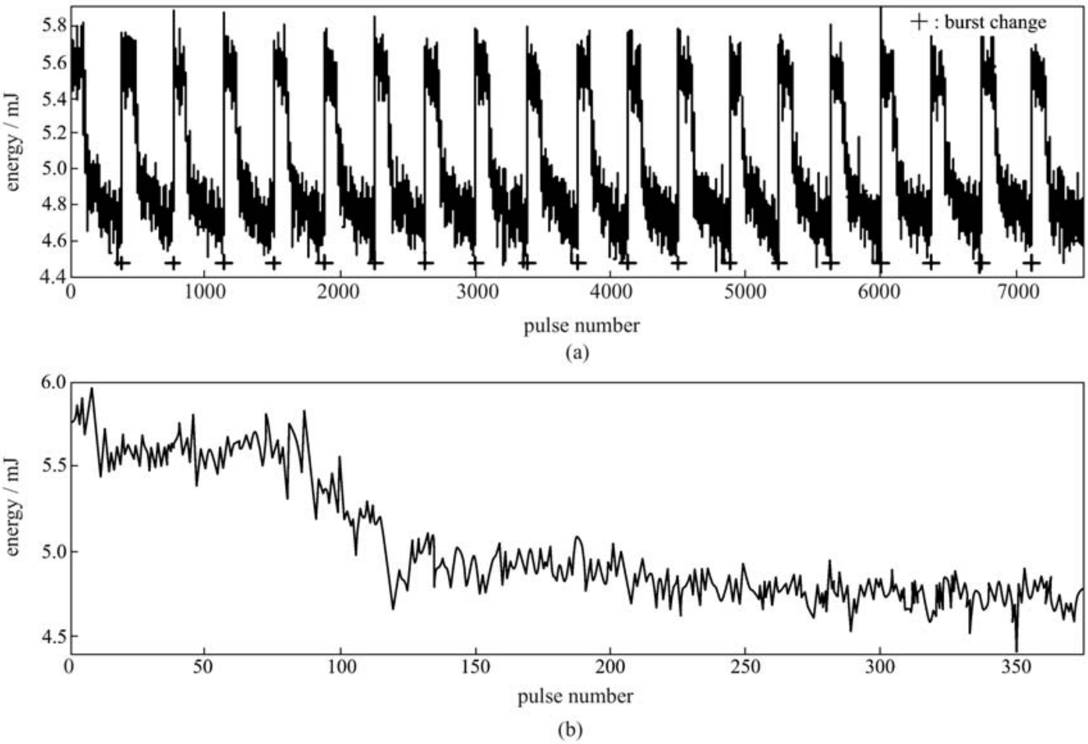

Fig. 3 Measured pulse-to-pulse energy fluctuation in constant HV mode with high voltage of 1690 V and repetition rate of 4 kHz. (a) History data of 20 bursts with 375 pulses in each burst; (b) history data of a single burst with 375 pulses

step-and-scan process of a lithography tool while Fig. 5(b) depicts the detail of a single exposure field. The values of relevant parameters in dose control algorithm are $N = 20$, $M = 5$, $k_s = 0.8$, and $k_o = 0.8$.

As shown clearly in Fig. 5, the effect of pulse-to-pulse energy stochastic fluctuation and energy overshot is reduced significantly with the real-time dose control algorithm in external high voltage mode. This effect is more obvious when observing the measured exposure dose obtained by moving averaging the energy of multiple pulses as shown in Fig. 6. The required dose shown in Figs. 6(a) to 6(f) are 5, 10, 20, 30, 40, and 50 mJ/cm^2,

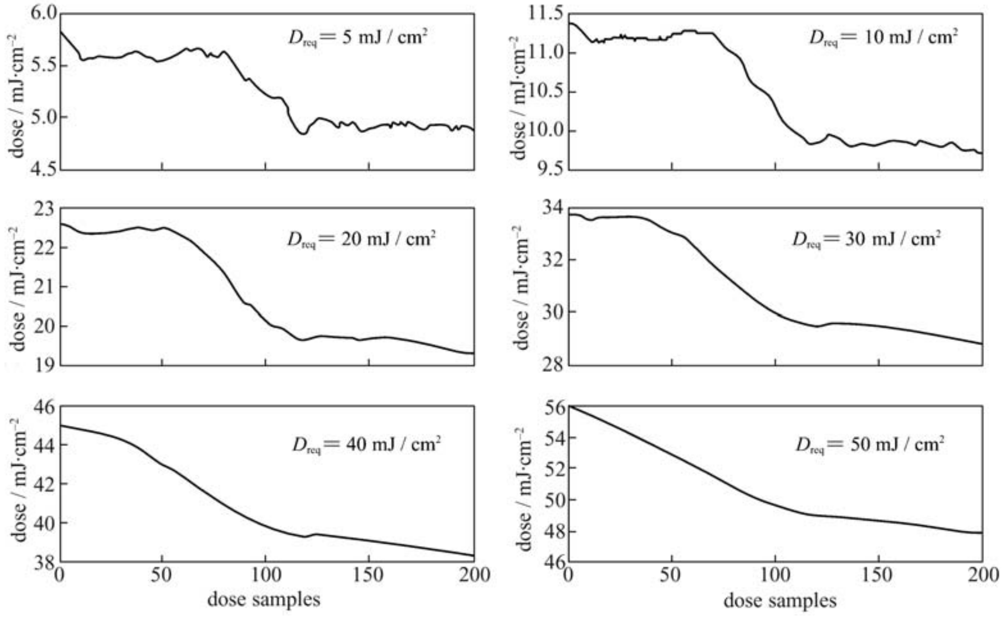

Fig. 4 Measured exposure dose during a scan exposure (constant HV mode)

Table 1 Statistical results of measured exposure dose (constant HV mode)

D_r/ mJ·cm^{-2}	number of pulses	D_{max}/ mJ·cm^{-2}	D_{min}/ mJ·cm^{-2}	σ/%
5.00	10	5.81	4.66	16.2
10.00	20	11.37	9.32	13.7
20.00	40	22.54	18.87	12.7
30.00	60	33.73	28.35	12.4
40.00	80	44.93	37.87	12.3
50.00	100	55.93	47.32	11.9

respectively, and the corresponding number of pulses in the slit are 10, 20, 40, 60, 80, and 100, respectively.

Table 2 depicts the statistical results of exposure dose measured in the experiment which was carried out under different dose requirements and in external HV mode. The exposure dose shown in Table 2 reaches a very high accuracy using the real-time dose control algorithm. The dose accuracy reaches 0.89% when the number of pulses N is 20. All the dose accuracy can meet the stringent dose requirement when N is larger than 20; the larger N is, the higher the dose accuracy that can be achieved. It is interesting to note that there is a remarkable improvement in dose accuracy in external HV mode compared to that in constant HV mode when the number of pulses is less than 10. However, the smoothing effect is not obvious with a dose accuracy of just 1.94% due to such a small required dose. This observation indicates that to fulfill dose accuracy requirements, the number of pulses must be larger than a certain critical value when optimizing the dose control parameters. Suppose that this condition cannot be satisfied by the optimization algorithm for dose control parameters, a variable attenuator has to be used to reduce the single pulse energy, which can increase the total number of laser pulses and thus increase the cost of ownership of the excimer laser.

4 Conclusions

A real-time exposure dose control algorithm for DUV excimer lasers in a step-and-scan optical lithography is presented, with the experiments conducted on an ArF excimer laser. The following conclusions are drawn:

1) The pulse-to-pulse energy of excimer lasers varies significantly with an extreme fluctuation up to 20%. This fluctuation can be characterized in two aspects, i.e., energy overshot and pulse-to-pulse stochastic fluctuation.

2) The exposure dose is the result of energy accumulation over a number of pulses. Although the effect of pulse-to-pulse stochastic fluctuation is significantly reduced by energy averaging over many pulses, due to

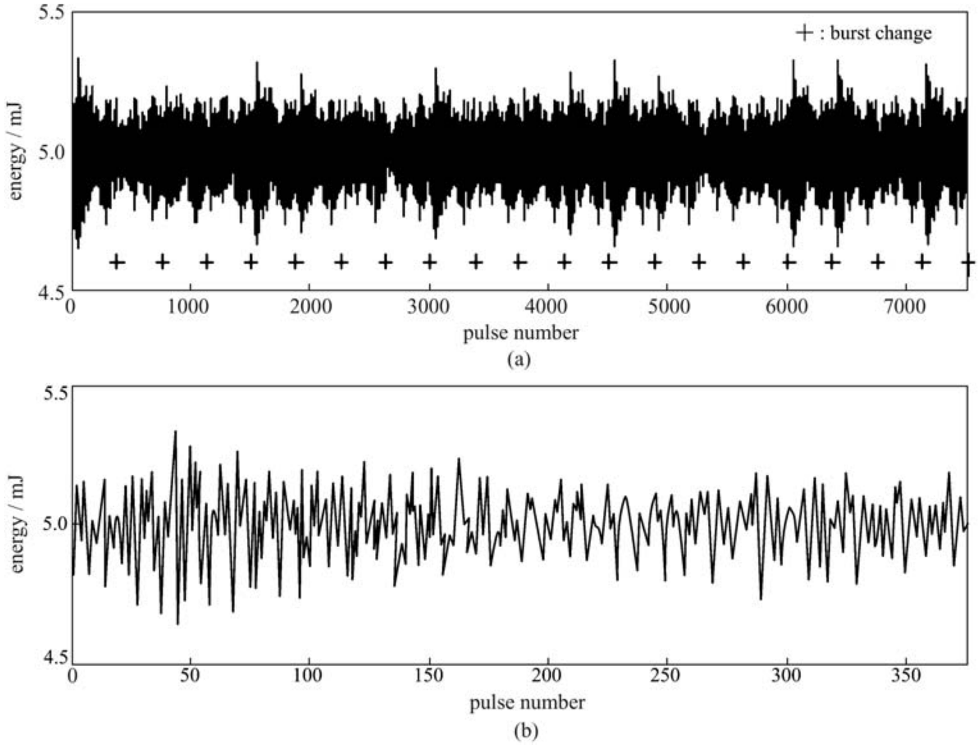

Fig. 5 Measured pulse-to-pulse energy fluctuation in external HV mode with proposed dose control algorithm and repetition rate of 4 kHz. (a) History data of 20 bursts with 375 pulses in each burst; (b) history data of a single burst with 375 pulses

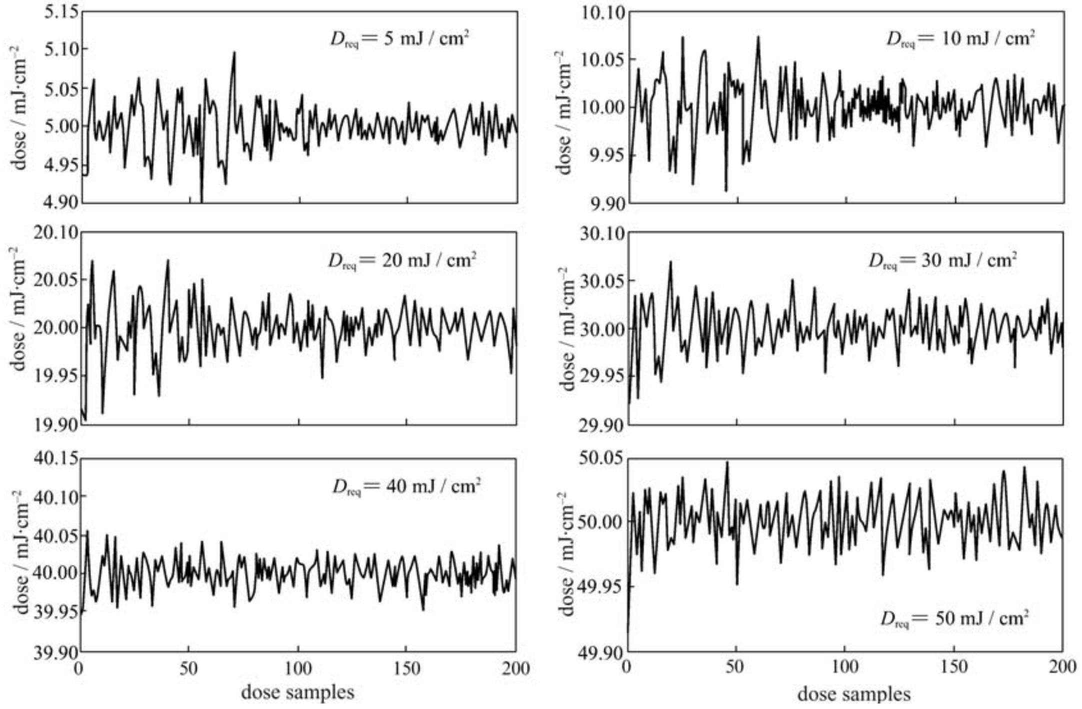

Fig. 6 Measured exposure dose during a scan exposure (external HV mode with dose control algorithm)

Table 2 Statistical results of measured exposure dose (external HV mode with dose control algorithm)

D_r/ mJ·cm^{-2}	number of pulses	D_{max}/ mJ·cm^{-2}	D_{min}/ mJ·cm^{-2}	σ/%
5.00	10	5.096	4.903	1.94
10.00	20	10.073	9.911	0.89
20.00	40	20.068	19.905	0.48
30.00	60	30.067	29.924	0.25
40.00	80	40.052	39.932	0.17
50.00	100	50.045	49.935	0.13

the existence of energy overshot, the dose accuracy achieved in constant high voltage mode is too poor to meet the dose accuracy requirement for sub-half-micron lithography.

3) The real-time dose control algorithm in external high voltage mode proposed in this paper is demonstrated not only to reduce the effect of pulse-to-pulse energy stochastic fluctuation significantly, but also to reduce the effect of energy overshot effectively. It is thus able to achieve a fairly high dose accuracy even with a small number of pulses.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant Nos. 50205009 and 50775090), Hi-Tech Research and Development Program of China (Grant No. 2006AA4Z325) and Program for New Century Excellent Talents in University of China (Grant No. NCET-06-0639).

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