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High precision and stability temperature control system for the immersion liquid in immersion lithography

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ABSTRACT

The temperature stability of immersion liquid is one of the main factors that affect the performance of the immersion lithography tool. Since the temperature control system of immersion liquid has the characteristics of time delays, full of disturbance and non-linear, the system and control algorithm should be carefully designed to control the temperature of the immersion liquid within the specification. In this paper, a control system of cascade structure with feed forward and lag compensation is proposed to reduce the time delays and the disturbance caused by the temperature fluctuation of ambient environment. Then, the mathematical model of the temperature control system is built, and the parameters of the model are obtained by 'gray' identification method. Based on the model, an algorithm which combines hierarchical control algorithm, integral separation PI algorithm, feed forward algorithm and lag compensation algorithm is designed. Last, experiments are conducted to evaluate the algorithm. The results show that the algorithm improves the robustness, compensates the time delays and reduces the overshoot. The system achieves a temperature stability of the immersion liquid within 22 ± 0.01 °C/30 mins, and it also has a good characteristic of anti-interference.

1. Introduction

Immersion lithography has been developed as an important approach to drive the resolution of optical lithography into 50 nm and below [1]. Due to the large refractive index of the immersion liquid, the NA (Numerical Aperture) of the lithographer, $NA = n sin\theta$, can be larger. And according to Rayleigh's rule, $r = k\lambda/NA$, the resolution will be smaller with large NA. In practice, the resolution of ArF immersion lithography can be smaller than 65 nm [2,3], and with MPL (Multiple Patterning Lithography) technology, the resolution can even reach sub 20 nm [4].

The high resolution of immersion lithography requires the high stability of the immersion liquid, especially the temperature stability, which is closely related to the stability of the refractive index, density, surface tension, and gas solubility [5]. According to Nikon's research, the temperature coefficient of the refractive index of the immersion liquid, dn/dT, is about $-2.0 \times 10^{-4}\ K^{-1}$, and the formation of bubble has a close relationship with the temperature variation of water [6]. And currently, the temperature stability requirement of the immersion liquid is at least within the range of 22 ± 0.01 °C/30 mins [7].

The temperature control or the thermal management is a hot topic in lithography. Nie et al. studied the temperature control system for the projection lens, he proposed a two inputs and two outputs nonlinear PI algorithm to improve the convergence speed and the steady state precision, and it achieved a high convergence speed and ± 0.006 °C temperature stability [8]. He et al. proposed a cascade-connected fuzzy PID feedback algorithm which controlled the temperature of immersion liquid by adjusting the flow rate of the PCW (Process Cooling Water) through heat exchangers [9]. Entegris proposed a re-circulating water bath method for the water purification system and a second stage "on-tool" temperature control system which served as a "polisher" that controlled the final temperature of immersion liquid close to the wafer in immersion lithography [5]. About the high precision temperature control of the liquid, Chinglain Chou from Stanford University proposed a steady state optimal control law which was composed of state feedback and time-dependent disturbance feedforward, and it controlled the shower oil temperature variance within 2.2 m °C [10].

However, there is little work about the temperature control system of the immersion liquid, and here we will study the system. First, the structure of the temperature system of cascade structure is proposed. Then the mathematical model of the system is built. To suppress the time-dependent disturbance, a smith predictor and a feedforward controller have also been added. Besides, a hierarchical control algorithm is adopted. Last, experiments are conducted to verify the system.

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2. The temperature control system of the immersion liquid

2.1. The immersion system in immersion lithography

The temperature control system is a subsystem of the immersion system which supplies the requirements satisfied liquid to the immersion hood. As shown in Fig. 2-1, the immersion system is composed of the degassing module which decreases the soluted gas in the liquid, UV module which sterilizes the liquid, ion/silica removal module which removes all the unwanted ions, filtration module which filters all the tiny particles, and the temperature control module (or system) which ensures the temperature stability of the liquid is within specification. Since the temperature of the liquid can be easily affected by other thermal factors, for example, environment changes and the self-heating element, so it is placed at the end of immersion system.

2.2. Temperature control system of cascade structure

The schematic of the temperature control system is shown in Fig. 2-2. The heat exchangers are used as the thermal control elements, and the outlet temperature of the heat exchanger can be controlled by adjusting the flow rate of PCW. Since there is a long pipe between the temperature measurement point T4 and the last servo valve, there will be serious time delays and the environment disturbance will be easily introduced. So a single loop controller is not enough and a cascade control structure, as shown in Fig. 2-3, is used. To achieve the high precision temperature control, FLUKE's NTC reference thermistor probe is used, its short-term repeatability is $\pm 0.006\ ^{\circ}\mathrm{C}$ and long term accuracy is better than $\pm 0.01\ ^{\circ}\mathrm{C}$.

The cascade control system consists of a fast-adjustment loop (inner loop) and main control loop (outer loop). Compared with the single feedback loop control configuration, the cascade control has following advantages in temperature control system [11]:

1) The sub controller is utilized to correct the disturbance arising within the inner loop before they can affect the controlled variable.
2) The effect of phase lag existing in the inner loop may be reduced by the sub controller, thus allowing the speed of response of the main loop to be improved.
3) The effect of parameter variation within the inner loop is corrected by the sub controller.
4) The effect of nonlinearity of the inner loop can be suppressed, especially when the time constant of two controllers is very different.

The temperature system can be simplified as shown in Fig. 2-3. The random disturbance from the first flow control valve and heat exchanger can be merged as the secondary disturbance to the pilot area. The pump, the second flow control valve and the long pipe to the immersion hood can be treated as the inert zone, and the load disturbance from the pump and environment temperature variation of this area can be viewed as the primary disturbance. The corresponding block diagram is shown in Fig. 2-4. The first flow control valve and heat exchanger in the fast adjusting loop can be simplified as $G_2(s)$ and the disturbance to these components can be viewed as $N_2(s)$. The pump, the second flow control valve and the long pipe can be simplified as $G_1(s)$, and the disturbance to these components is simplified as primary disturbance $N_1(s)$.

2.3. Improved cascade control structure

Cascade control structure can improve the system's respond speed and has the ability to suppress the secondary disturbance to the inner loop. However, the primary disturbance to the system is from the temperature fluctuation of the ambient environment which is in the outer loop, and the cascade control can do nothing to suppress it. As shown in Fig. 2-5, when the environment temperature varies about 1.5 °C, the fluctuation of the output temperature exceeds 0.05 °C, which cannot be ignored when compared with the stability specification.

To suppress the primary disturbance, which is mainly the environment disturbance, in the outer loop, an environment feedforward controller is added to the cascade control system. The

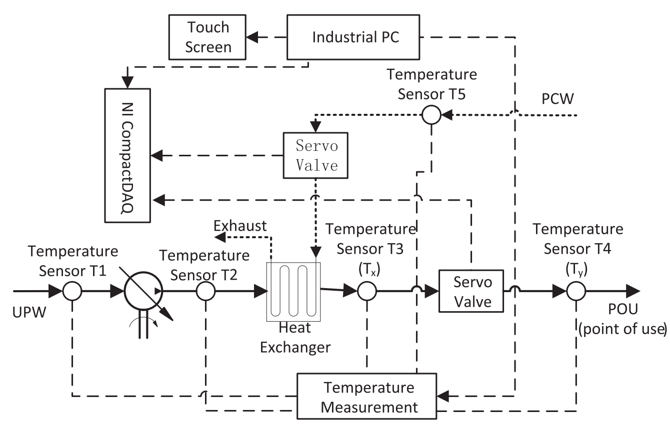

Fig. 2-2. Schematic of the temperature control system.

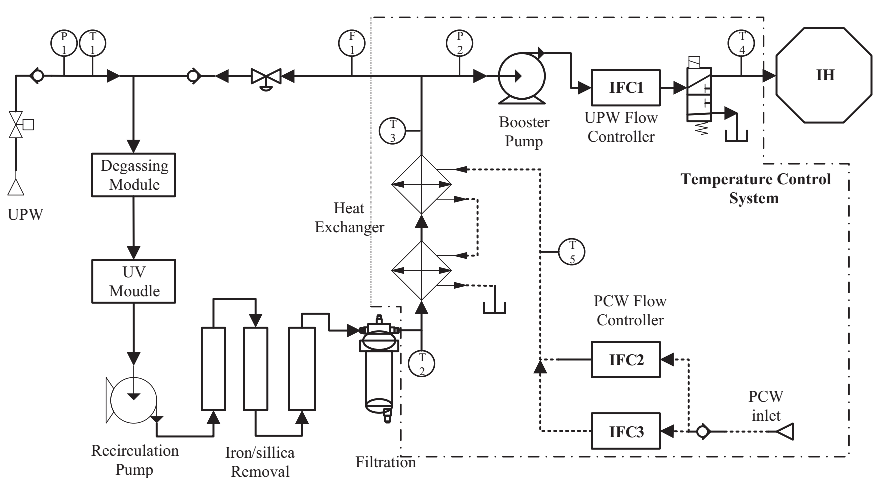

Fig. 2-1. The schematic of the immersion system of immersion lithography.

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