Silicon wafer cooling by low pressure helium gas in vacuum environment

Shinsuke Udagawa[1], Satoshi Takahashi[2], Daisuke Nakamura[3], and Kazuo Maeno[1]

1. Chiba University (1-33 Yayoi, Inage, Chiba 263-8522, Japan)
2. Nikon corporation (1-6-3 Nishi-Ohi, Shinagawa, Tokyo 140-8601, Japan)
3. Dai Nippon Printing Co., Ltd, (2-2-1 Fukuoka, Fujimino, Saitama 356-8507, Japan)

Abstract. On the lithography process of sub 45nm, ML2 (Maskless Lithography) and EUVL (Extreme Ultra Violet Lithography) have mainly been noticed as next generation lithography exposure tools. Developing these tools is crucial. These methods have high exposure energy, and local thermal deformation by the exposure energy causes pattern placement error or image defocusing directly. As a consequence, the deterioration of throughput is induced. Therefore, decreasing the local thermal deformation in these methods is key issue. Consequently, the low pressure inert gas introduction between wafer backside and the chuck for improving the cooling effect is considered highly probable. In addition, increased temperature of silicon wafer during the exposure remains near the room temperature. The cooling effect and heat transfer characteristics have not been discussed precisely in these schemes. We concentrate to decrease the local thermal deformation, and to the validation of the cooling effect or comprehending of the heat transfer characteristics. In the previous study we have developed an experimental apparatus, where we can estimate the heat transfer characteristics at the low pressure region, with assumed chuck system of next generation lithography exposure tools. In this paper we calculate the thermal accommodation coefficient between low the helium gas and the silicon wafer by using experimental results and Finite Element Method (FEM) analysis.

Keywords: next generation lithography, heat transfer coefficient, thermal accommodation coefficient, silicon wafer.
PACS: 44.90.+c

INTRODUCTION

According to the ITRS 2005 version, the circuit line width of DRAM has been matched 65nm design rule at half pitch in 2007. The design rule now shifts to make translations to 45nm at half pitch on the further roadmap on 2010[1]. On the lithography process DRAM has aimed at integrating to make miniaturization of the circuit line width by using the short wavelength of exposure light source, or refining the various peripheral technologies. On the other hand, there are various requires such as high-mix and low-volume production with low cost for lithography technique on large quantity production in recent years. In addition, the optical lithography which is a mainstream technology of commercial production has great influence on the production of semiconductors by increasing the cost of development with soaring cost of mask. On the lithography process of sub 45nm, ML2 (Maskless Lithography) as high-mix and low-volume production, and EUVL (Extreme Ultra Violet Lithography) as the large quantity production have been noticed mainly as next generation lithography exposure tools. Developing of these technologies is crucial as mentioned above. As for ML2, laser or low energy electron beam (EB) will be used as the exposure beam source. They have high exposure energy, and the local and thermal deformation of irradiated material surface by the energy causes the pattern placement error or image defocusing directly. As a consequence, they induce the deterioration of throughput. Therefore, decreasing the local and thermal deformation is key issue. The one method of decreasing the local and thermal deformation is improving the heat conduction to the chuck on the EUVL, which was discussed by Chang[2]. Reducing the deformation, the low pressure inert gas introduction between wafer backside and chuck is considered highly probable for improvement of the cooling effect. In addition, the increased temperature of silicon wafer during the exposure ranges rather low near the room temperature, where the cooling effect and heat transfer characteristics on the wafer by low pressure gas have not been discussed precisely.

We concentrate to decrease the local and thermal deformation of silicon wafer during the exposure, and to the clarification of the cooling effect by low pressure gas and the heat transfer characteristics. In the previous study we have developed the experimental apparatus which make us estimate the heat transfer characteristics at the low pressure region with the chuck system of next generation lithography exposure tools. From the experimental data we obtained the thermal accommodation coefficient between low pressure helium gas and aluminum alloy[3]. In this paper the thermal accommodation coefficient is experimentally obtained between silicon wafer and low pressure helium gas. We have performed the on the temperature variation experiment with silicon wafer as the solid material and helium which is well known monatomic and high thermal conductivity gas by using experimental apparatus, which was developed for the objects of constructing of the novel wafer chuck systems with cooling effect under such gas condition in the next generation lithography exposure tools previously. Then we calculate the thermal accommodation coefficient between low pressure helium gas and silicon wafer by using our experimental results and FEM solutions.

HEAT TRANSFER CHARACTERISTICS BY RAREFIED GAS MOLECULE

The quantity of heat transfer Q in steady states between two parallel plates separated by a distance (gap length) d can be expressed as follows by Newton's cooling low

$$Q = hA(T_2 - T_1), \quad (T_2 > T_1), \tag{1}$$

where A is heat transfer area of both plates and T_1,T_2 are the temperatures at each plates. Heat transfer coefficient h, which represents thermal characteristics of gas and solids, at a regime of the low pressure gas is represented by Smoluchowski as a following relation of the form[4], which is including the effect of the temperature jump.

$$h = \frac{k}{d + 2g}, \tag{2}$$

$$k = \varepsilon \eta c_v, \quad g = \frac{2-\alpha}{\alpha}\frac{2\varepsilon}{\gamma+1}\lambda, \quad \varepsilon = \frac{9\gamma - 5}{4}, \tag{3}$$

where k is the mean conductivity over the range T_2 to T_1, η is the viscosity coefficient, c_v is the specific heat at constant volume, and γ is specific heat ratio at constant pressure to that at constant volume. In these equations α has the value

$$\alpha = \frac{\alpha_1 \alpha_2}{\alpha_1 + \alpha_2 - \alpha_1 \alpha_2}, \tag{4}$$

where α_1 and α_2 are the values of the thermal accommodation coefficient introduced by Knudsen for each surfaces of the two parallel plates. The mean free path λ of molecules under Maxwell-Boltzmann distribution laws for molecular velocities is given by

$$\lambda = \frac{1}{\sqrt{2}\pi n \delta^2}, \tag{5}$$

where δ is molecular diameter, n is number of density of gas and has the form

$$n = \frac{p}{\kappa T_g}, \tag{6}$$

where p is gas pressure, κ is the Boltzmann constant, and T_g is the absolute temperature of gas. In the regime of low pressure gas (λ~d), h depends on both p and d due to above equations.

EXPERIMENTAL APPARATUS AND SET UP

The experimental apparatus on the heat transfer characteristics for low pressure gas of normal temperature is shown in Fig.1a. The aluminum disc or silicon wafer, which has 100mm diameter and 500μm thickness, is adhered on the solid surface by UV curable resins onto the Pyrex ring. The gap length d is taken from 200 to 900μm by exchanging the spacers between the Pyrex ring and aluminum cooling plate. The gas pressure p is set up 0, 133, 339, and 655Pa using a mass flow controller (MFC) installed at gas inlet. The Knudsen number range of our experiment is of Kn=0.03~0.71, where the flow regime is intermediate between continuum (Kn<0.01) and free molecular flow (Kn>10), provided that $\kappa=1.38\times10^{-23}$J/K, T_g=296K and helium molecular diameter $\delta=2.2\times10^{-10}$m. Environmental temperature of aluminum cooling plate is set to 296K. Gap sensors are settled for the measurement of gap length displacements occurring by the flexure of aluminum disc or silicon wafer due to the gas pressure which is filled between the disc or wafer and the cooling plate. The UV light is used as a heat source, and the aluminum disc or silicon wafer is cooled by the low pressure helium gas. The temperature rising data are measured by 3 wires platinum RTD (Resistance Temperature Detector) sensors, which are arranged as shown in Fig.1b on the aluminum disc and silicon wafer surface. The heat flux imposed by the UV light is approximately 800W/m^2 and 2500W/m^2 on to the exposure area for the aluminum disc and silicon wafer respectively. The UV light radiation time is 700sec. The apparatus of Fig.1a is placed in a vacuum chamber, whose pressure is less than 1.3×10^{-2}Pa.

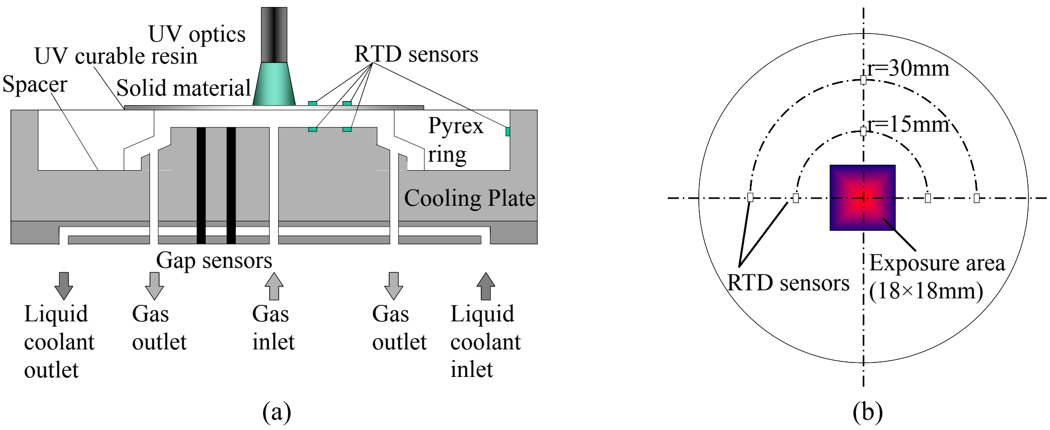


FIGURE 1. (a) Schematic diagram of experimental apparatus, (b) RTD sensors arrangement and exposure area on 100mm-diameter solid materials

Firstly, we have to obtain the value of α_1 and α_2 which are the thermal accommodation coefficient between aluminum disc surface or cooling plate and low pressure helium gas respectively. The cooling plate surface is similar in roughness to aluminum disc back side surface because the values of α_1 and α_2 are predicted to be the same. The experiment by using an aluminum disc to calculate the thermal accommodation coefficient between aluminum disc surface and low pressure helium gas is firstly carried out. After knowing the thermal accommodation coefficient, we have performed the experiment to calculate through the similar estimation of the thermal accommodation coefficient between silicon wafer surface and low pressure helium gas by using a silicon wafer as the solid surface.

HEAT TRANSFER BY FEM ANALYSIS

We have performed the numerical simulation to obtain the heat transfer coefficients between solid material and low pressure helium gas because of impossible to calculate the heat transfer coefficient only experimental temperature data. The temperature jump was not considered in this simulation.

A transient, thermal, and numerical model shown in Fig.2a has been used to obtain the heat transfer coefficients of low pressure helium gas by curve fitting for experimental results. The system of aluminum disc or silicon wafer, Pyrex ring and cooling plate is composed of 8 noded, 3 dimensional and thermal solid elements. Numerical simulation of FEM is also performed by using I-DEAS TMG Thermal Analysis (MAYA Heat Transfer Technologies Limited, CANADA). The material properties are shown in Table 1. Boundary conditions which are shown in Fig.2b are set depending upon the modeled gas pressure condition.

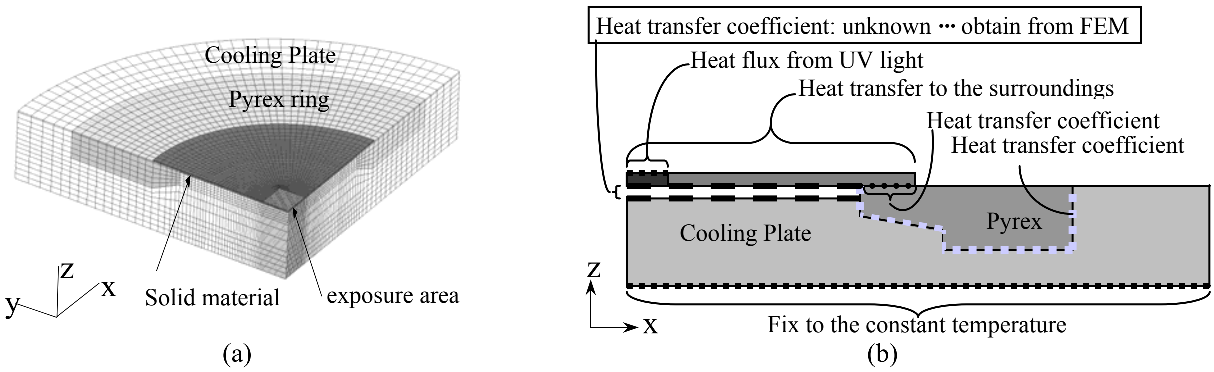


FIGURE 2. (a) Heat transfer FEM model, (b) Boundary conditions of FEM analysis

The radiation conditions are imposed on the top surface of aluminum disc or silicon wafer as ε_{Al}=0.15 or ε_{Si}=0.127, respectively. The condition of heat transfer coefficient of the UV curable resin is determined as 800W/m^2 □K for the case of aluminum disc and 400W/m^2·K for the case of silicon wafer, and contact heat transfer coefficient between Pyrex ring and cooling plate is 15W/m^2·K. Environmental and bottom surface temperatures of the cooling plate are fixed to 296K, and insulated conditions are given on the symmetrical surfaces for all models. Firstly, confirming our FEM model, boundary conditions, and material properties, we have performed a simulation using our FEM model for the case without filling helium gas, where the heat transfer condition between the solid materials and the cooling plate was obtained as the heat emissivity. After confirming our FEM model, boundary conditions, and material properties, the uniform heat transfer conditions between the solid materials and the cooling plate are imposed for the case of several helium gas pressures. The heat transfer coefficients of the low pressure helium gas are determined by curve fitting method by using simulated solution for experimental results.

TABLE 1. Material properties for heat transfer analysis

Material	**Density** ρ **kg/m^3**	**Thermal conductivity** k_s **W/m·K**	**Specific heat** c_v **J/kg·K**
Aluminum disc	2680	138	921
Silicon wafer	2330	138	701
Pyrex ring	2230	1	730
Cooling plate	2720	172	921

FEM AND EXPERIMENTAL RESULTS

Figures 3(a) and (b) shows an example of the transient experimental temperature rise data using the aluminum disc and silicon wafer at *r*=15mm in the RTD sensor positions for several gas pressures, respectively.

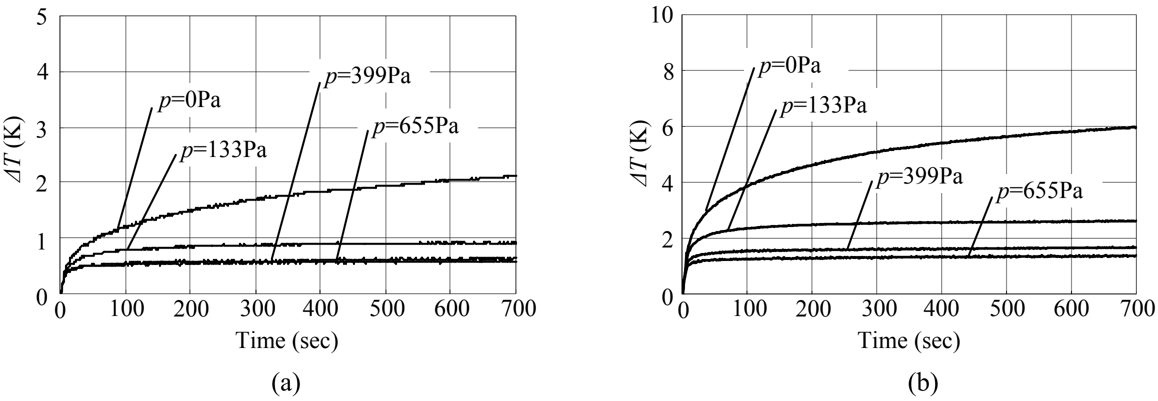
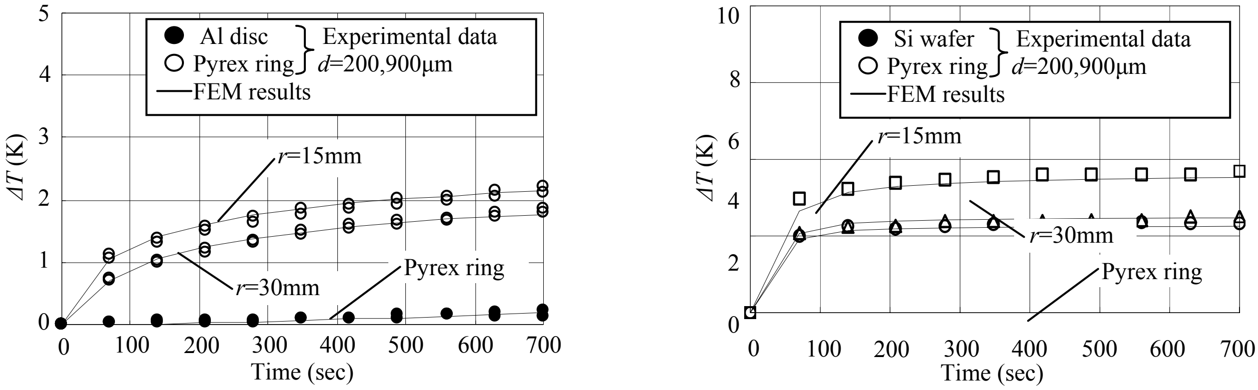


FIGURE 3. (a) Experimental temperature rising data of aluminum disc for several helium gas pressures. (*d*=200μm)
(b) Experimental temperature rising data of silicon wafer for several helium gas pressures. (*d*=200μm)

We can confirm that the temperature rising rate decreases as helium gas pressure increases for both case. We can also confirm that the temperature rising for the case of silicon wafer is larger than the case of aluminum disc. The difference of the reflectivity for the regime of UV wavelength seems to cause the difference between both cases.

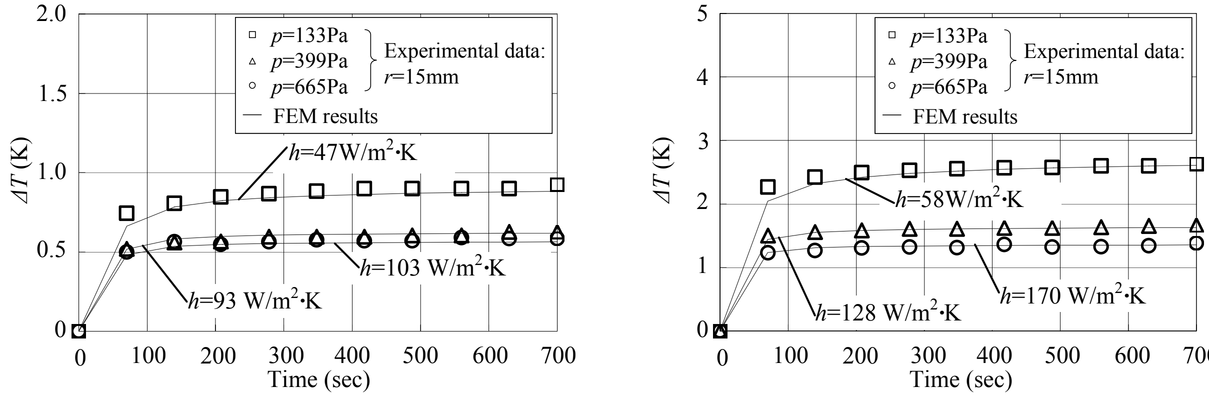
Figures 4a and 4b show the FEM analysis for our experimental results on aluminum disc and silicon wafer for p=0, respectively. From Figs. 4a and 4b the good agreement between the experimental and FEM results can be obtained for both cases. From theses results, we have confirmed the validity of our FEM model.



(a) (b)

FIGURE 4. (a) FEM results for experimental data on aluminum disc for p=0, (b) FEM results for experimental data on aluminum disc for p=0

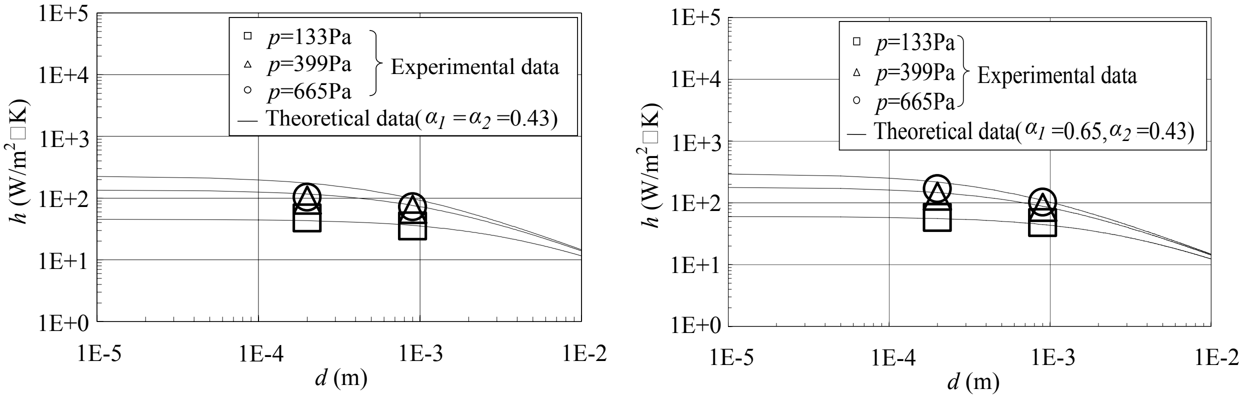
Figures 5a and 5b show the FEM analysis for the experimental results at d=200µm and r=15mm on aluminum disc and silicon wafer for several gas pressures, respectively. From these results the heat transfer coefficients for several gas pressures are obtained. For both cases the heat transfer coefficients for several gas pressure conditions at d=200µm are obtained respectively. Similarly, the heat transfer coefficients at d=900µm are also obtained.



(a) (b)

FIGURE 5. (a) FEM results for experimental results at d=200µm and r=15mm on aluminum disc for several helium gas pressures, (b) FEM results for experimental results at d=200µm and r=15mm on silicon wafer for several helium gas pressures

From the obtained heat transfer coefficients between aluminum disc and low pressure helium gas by using FEM analysis for experimental data, we can compare with the obtained data and theoretical data, which were represented by heat transfer equations (2) to (6), as shown in Fig. 6a. The obtained heat transfer coefficients between aluminum disc and low pressure helium gas show good agreement with theoretical data at α_1=α_2=0.43, except for high pressure and short distance condition, which was originated by the flexure of aluminum disc caused by increasing the gas pressure. Similarly, after knowing the value of α_2, we can obtain the value of α_1, which is the thermal accommodation coefficient between silicon wafer and low pressure helium gas, as shown in Fig. 6b. The obtained heat transfer coefficients between silicon wafer and low pressure helium gas show good agreement with theoretical data at α_1=0.65 and α_2=0.43. We can see agreement even at high pressure and short distance condition, compared with the case of aluminum disc. These differences originate from the difference of material properties such as Young's module and Poisson's ratio.



(a) (b)

FIGURE 6. (a) Relation between heat transfer coefficient *h* and distance between aluminum disc and cooling plate *d* for several gas pressure of helium, (b) Relation between heat transfer coefficient *h* and distance between silicon wafer and cooling plate *d* for several gas pressure of helium

CONCLUSIONS

In this paper for the thermal accommodation cefficient between silicon wafer and low pressure helium gas of normal temperature, we have performed the experiment by using a heat-transfer measuring apparatus and the simulation by using FEM, which makes us obtain the heat transfer coefficients for experimental results. After that, we have obtained the thermal accommodation coefficient, which can be compared with the theoretical data represented by equation (2) to (6) and heat transfer coefficient obtained from FEM data. From our results and discussion the following points are concluded.

1. The heat transfer coefficients between aluminum disc or silicon wafer and low pressure helium gas of normal temperature has been obtained for experimental results by using FEM analysis without considering the temperature jump.
2. These obtained heat transfer coefficients between aluminum disc and low pressure helium gas show good agreement with theoretical data, which are represented by heat transfer equation (2) to (6) including the temperature jump at α_1=α_2=0.43, except for high pressure and short distance conditions (*p*=399, 665Pa).
3. These obtained heat transfer coefficients between silicon wafer and low pressure helium gas also show good agreement with theoretical data at α_1=0.65 and α_2=0.43.
4. The future plan includes to compare with the results from this study and the results which will be obtained by numerical simulation for Boltzmann equation with BGK model, and the thermal accommodation coefficients which will be calculated by using the equation which was represented by Bassanini[5].

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