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Daisuke Miyagi* Aisya Saitou† Norio Takahashi‡
Naoki Uchida** Kazuhiro Ozaki††

*Okayama University
†Okayama University
‡Okayama University
**Mitsui Engineering & Shipbuilding Company Limited
††Mitsui Engineering & Shipbuilding Company, Limited

Improvement of Zone Control Induction Heating Equipment for High-Speed Processing of Semiconductor Devices

Daisuke Miyagi[1], Aisya Saitou[1], Norio Takahashi[1], *Fellow, IEEE*, Naoki Uchida[2], and Kazuhiro Ozaki[2]

[1]Department of Electrical and Electronic Engineering, Okayama University, Okayama 700-8530, Japan
[2]Advanced Machinery and Systems Department, Mitsui Engineering and Shipbuilding Co., Ltd., Tamano 706-8651, Japan

In order to process a semiconductor device of high quality, uniform heating is necessary, but it is not easy to heat uniformly with conventional induction heating equipment. To solve this problem, zone control induction heating equipment has been jointly developed. In this paper, we examine the effect of dividing an induction heater into several small coil groups having different current and frequency, using the finite-element method. We describe the heating characteristics of the zone control coil groups and show that nearly uniform heating is possible by controlling both current and frequency.

Index Terms—**Induction heating, uniform heating, zone control.**

I. Introduction

A quick, highly precise, high temperature and uniform heating method is needed for processing a semiconductor wafer used for a photovoltaic cell. There are several heating methods, such as induction heating, lamp heating, and resistance heating. In the lamp heating and resistance heating, the high temperature heating and quick heating are difficult respectively. On the contrary, the induction heating [1] has advantages of quick and high temperature heating. Therefore, the induction heating is a promising method for the processing of a wafer. But how to realize a uniform heating is a problem. In order to realize uniform heating of the wafer, it is necessary to supply the electric energy uniformly to the graphite. When only one exciting coil is used in the induction heating, the temperature in the graphite cannot be controlled. Then, a new technique called zone control (shown in Fig. 1) is introduced. In the technique, the exciting coil is divided into several small coils and each coil is connected to an independent power supply of high frequency, and the current and frequency in each coil are controlled to realize a uniform heating. The characteristic of zone control when only currents are controlled has been reported in a previous publication [2]. In the current control heating equipment, the current of coil above the center of the graphite should be extremely large and that above the edge should be small, because the eddy-current loss at the center of graphite is much smaller than those of other parts. Such a large unbalance of the current of each coil is not acceptable for practical use. Then, frequencies of each coil were also controlled in order to decrease the current of the coil above the center of the graphite.

In this paper, the effect of each coil on heating characteristics is examined using the finite-element method (FEM), and the heating properties without zone control and that with zone control are compared each other. Both eight-zone and 12-zone models are examined. The useful information for controlling current and frequency, which realize the uniform heating, is obtained.

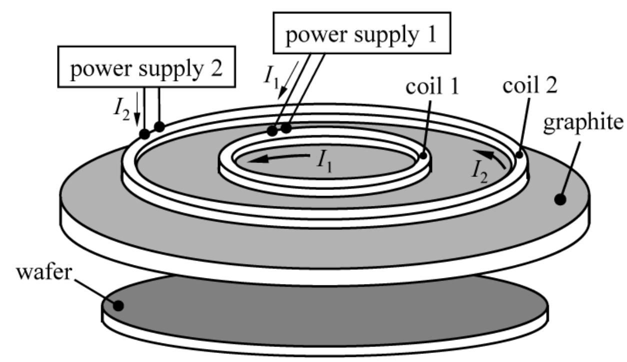

Fig. 1. Induction heating equipment with zone control. (a) Eight-zone model: the heating coil is divided into eight zones and the graphite is divided into eight regions (p_1–p_8). (b) Twelve-zone model: the heating coil is divided into 12 zones and the graphite is divided into 12 regions (q_1–q_{12}).

II. Analyzed Model

A. Zone Control Induction Heating Equipment

Fig. 2 shows analyzed models of zone control induction heating equipment. For example, in the case of the eight-zone model shown in Fig. 2(a), the heating coils are divided into eight zones, and these are connected to the high frequency inverters. The graphite is set just under the excitation coils and is heated by the eddy-current loss produced by the exciting coils. The current and frequency of each exciting coil is changed in order to obtain a uniform distribution of eddy-current loss in each region of the graphite. The eddy current is taken into account in the graphite, wafer, core, and exciting coils. Each material constant is shown in Table I.

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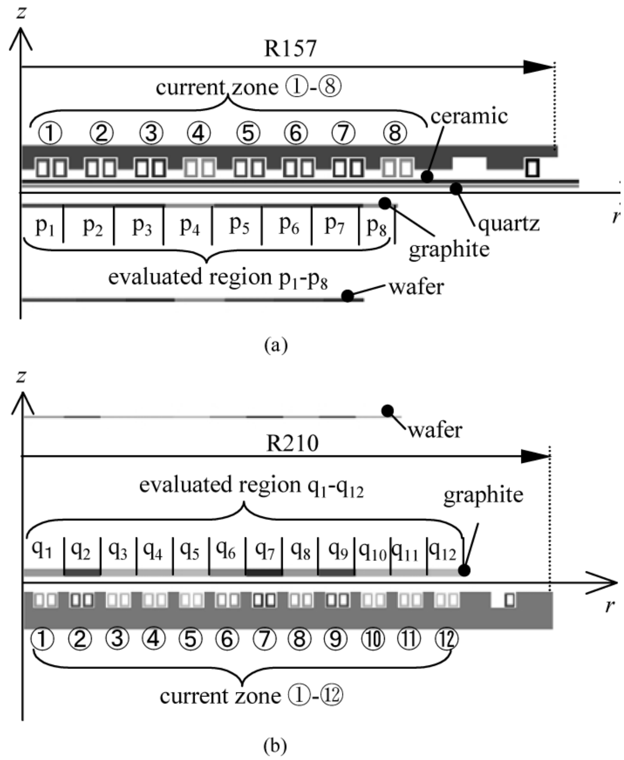

Fig. 2. Analyzed models.

TABLE I
MATERIAL CONSTANT

Material	Relative permeability	Conductivity (S/m)
Graphite	1.0	1.1236×10^{5}
Wafer	1.0	9.09×10^{3}
Core	32.0	2.5×10^{-2}
Exciting coil	1.0	5.0×10^{7}

B. Governing Equation

The governing equation of eddy-current problem is as follows:

$$\mathrm{rot}\left(\frac{1}{\mu}\,\mathrm{rot}\,\dot{\boldsymbol{A}}\right) = \dot{\boldsymbol{J}}_0 - j\omega\,\sigma\dot{\boldsymbol{A}} + \sigma\,\mathrm{grad}\,\phi \qquad (1)$$

where μ is the permeability, $\dot{\boldsymbol{A}}$ is the magnetic vector potential, $\dot{\boldsymbol{J}}_0$ is the impressed current density, σ is the conductivity, and ϕ is the electric scalar potential. The dot $(\,\dot{}\,)$ denotes a complex variable. As the core is not saturated, the phasor method (the so-called $j\omega$ method) is applied in the axisymmetric eddy-current analysis by assuming that the magnetic characteristic is linear.

III. Results and Discussion

Fig. 3 shows the flux distribution of the eight–zone model when the same current (100 A) and frequency (40 kHz) are impressed in all coils. The flux density at the edge of the graphite is high due to the skin effect. Therefore, the eddy-current loss is not uniform in the graphite. The eddy-current loss at the edge of the graphite is larger than that at the center of the graphite.

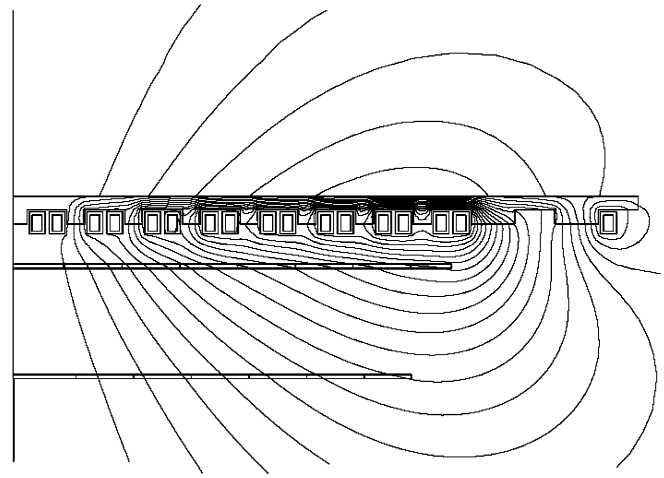

Fig. 3. Flux distribution when the amplitude of current and frequency are same in all coils (eight-zone model).

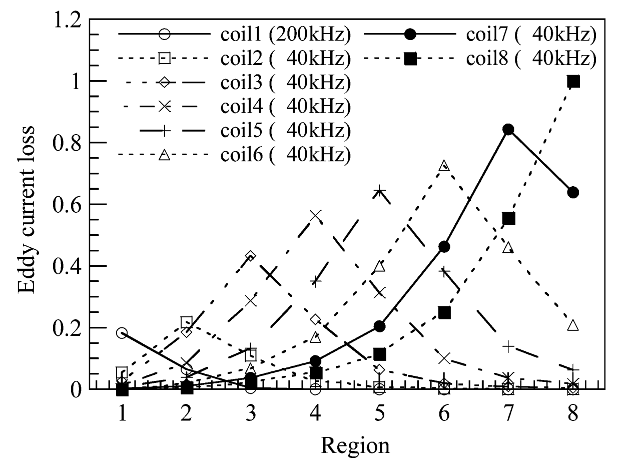

Fig. 4. Distribution of eddy-current loss when only one coil is excited.

Fig. 4 shows the distribution of eddy-current loss of eight-zone model when only one coil is excited. In the case of Fig. 4, the eddy-current loss becomes maximum at region p_8 in the graphite, when only coil 8 is exited. The maximum value of the amplitude of eddy-current loss (W/mm^2) in the graphite (evaluated region p_8) is normalized to unity. The frequency of coil 1 (inner part) (200 kHz) is increased compared with those of other coils (40 kHz), because the eddy-current loss density is considerably smaller than other part due to the skin effect. But, the distribution of eddy-current loss is not uniform. Fig. 5 shows the effect of frequency of coil 2 on distribution of eddy-current loss. Fig. 5 suggests that the distribution of eddy-current loss can be improved by changing the frequency of inner coil, such as coil 2, to a higher value.

We studied the relationship between the current and the frequency of each coil and the eddy-current loss in each region by using FEM when only one coil is exited. The coefficients which represent the relationship between the exciting current of each coil and eddy-current loss are obtained using the results in Fig. 4. Then, the optimal current of each coil to realize a uniform heating is obtained by using those coefficients. Fig. 6 shows the exciting current of each coil of eight-zone model with zone control. The exciting current of coil 1 is increased

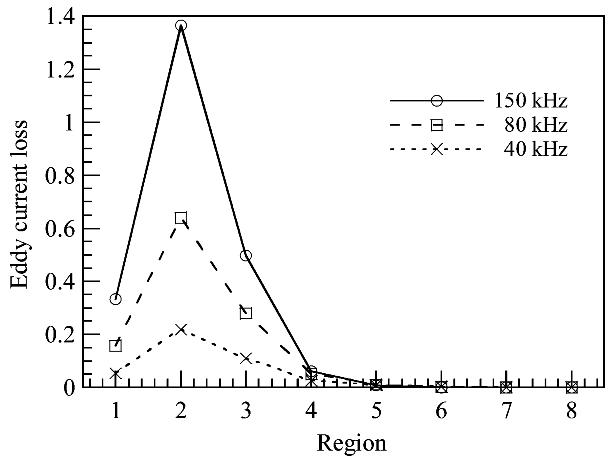

Fig. 5. Effect of frequency of coil 2 of eight-zone model on distribution of eddy-current loss.

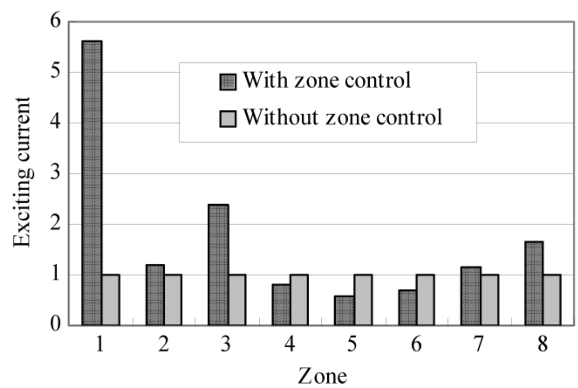

Fig. 6. Exciting current in each coil (eight-zone model).

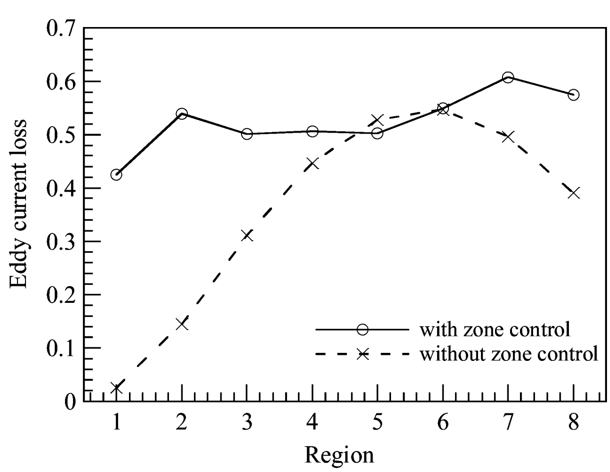

Fig. 7. Distribution of eddy-current loss of eight-zone model with and without zone control (3.0 mm thick graphite).

because the eddy-current loss of region p_1 without zone control is low. Fig. 7 shows distributions of eddy-current loss in the graphite with zone control and without zone control of the eight-zone model. Fig. 8 shows the distribution of eddy-current loss of 12-zone model with zone control. Regardless of the thickness of the graphite, uniform distribution of eddy-current

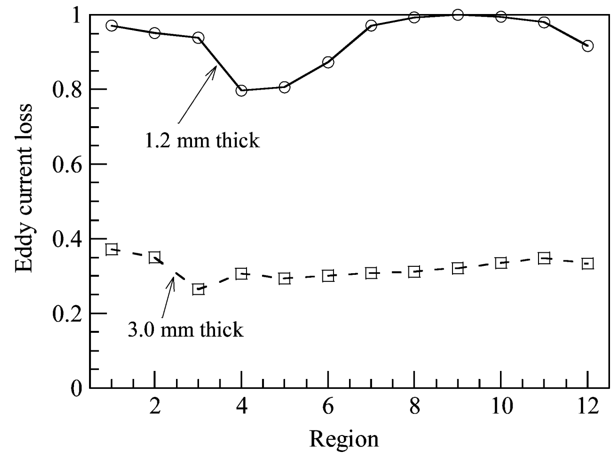

Fig. 8. Distribution of eddy-current loss of 12-zone model when both frequency and current are controlled (1.2 mm and 3.0 mm thick graphite).

loss in the graphite can be obtained by controlling the exiting current in each coil. The eddy-current loss becomes maximum in the case of 12-zone model (1.2 mm thick graphite) as shown in Fig. 8. The maximum value of the amplitude of eddy-current loss (W/mm^2) in the graphite is normalized to unity. A nearly uniform distribution of eddy-current loss in the graphite can be obtained without extreme unbalance among exiting currents of each coil.

IV. Conclusion

A new technique called zone control is introduced in the induction heating equipment for high-speed processing of semiconductor. The effect of dividing into several small coil groups having different current and frequency on heating characteristics is investigated using FEM. It is shown that a nearly uniform heating of graphite is possible by controlling the exciting current and frequency of each coil. The zone control induction heating equipment is very useful for uniform heating.

Acknowledgment

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Manuscript received February 7, 2005; revised April 30, 2005 (e-mail: miyagi@elec.okayama-u.ac.jp).