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IMPROVEMENT OF ZONE CONTROL INDUCTION HEATING APPLICATOR USED FOR PROCESSING CIRCULAR SEMICONDUCTOR DISCS

BY

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Abstract. An improvement in the performance of the zone-control induction heating applicator used for heating semiconductor wafers is proposed, by using two magnetic discs that shield the device and a system of 12 coils that expand in the direction of highest power density non-uniformity. The objective functions are the heating non-uniformity factor (to be minimized) and the total absorbed power (to be maximized). A simpler version of the zone-control technique which uses only one control variable, the current amplitude in the outer coils, used in this paper for the design with two magnetic discs, renders satisfactory results in terms of both objective functions.

Key words: induction heating; optimization methods; semiconductor wafer; zone-control.

1. Introduction

The main technique employed for high speed processing of semiconductor wafers, that are used, for example, in the fabrication of photovoltaic cells, is *induction heating*. High temperatures and short heating times are the principal advantages of this method. Since the semiconductor wafer is usually a thin circular disc which has, in industrial applications,

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standard sizes, the first choice of induction heating equipment is one that uses a set of coils coaxial with the disc to be heated, fed by sinusoidal currents of high amplitudes and high frequency, in the range of 1 to 200 kHz. The main objective is to obtain an almost uniform heating of the wafer and graphite disc that radiates heat to the wafer. An acceptable degree of uniformity can be obtained if the amplitudes and frequencies of the coil currents and the number of coils are carefully chosen.

This optimization problem can be considered as a mono-objective one, if only the temperature, and thus the power density uniformity throughout the domain is sought, or it may involve other objectives, such as the maximization of the total power dissipated in the load and possibly the minimization of the magnetic field in a target zone (the human operator zone), thus becoming a multi-objective optimization problem. These goals are in conflict since the current distribution that minimizes the power non-uniformity leads to smaller dissipated powers in the semiconductor and thus to larger heating times.

A new concept called *zone control* was introduced by Okamoto *et al*., (2004), and further developed by Miyagi *et al*., (2006). The concept focuses on monitoring the power level in a number of domains (zones) that extend in radial direction in the wafer, the number of zones being equal to the number of exciting coils. Both these studies address a mono-objective optimization with respect to the power non-uniformity throughout the monitored domains, using evolutionary strategies and considering the amplitude of the currents in the coils as design variables. Fujita *et al*., (2011), have performed a theoretical analysis of the zone control induction heating system (ZCIH), establishing that a phase control of the coil current is necessary in order to adjust the amplitude of the currents in a wide range and focusing on a six zone prototype. In our previous studies (Petrescu, 2012; Petrescu *et al*., 2013) the induction heating device, based on zone control, was investigated carrying both a mono-objective and a multi-objective optimization and redefining the objective function for power uniformity.

The present paper considers a modified design from that analysed in the fore-mentioned papers that uses magnetic discs and two levels of power monitoring in the semiconductor. A simple control scheme for the amplitude of currents is used and the effect of frequency and of some topological parameters on the power non-uniformity and on the total absorbed power is investigated.

2. Physical Model of the Applicator

The schematic model of the induction heating device with axial symmetry is presented in Fig.1. A system of *N* coils, each with two wires of rectangular cross-section, is placed on a quartz plate. The amplitude of the sinusoidal currents, I_1,.., I_N, having the frequency *f*, may be adjusted independently in each coil. Beneath the quartz plate the graphite plate and the thin wafer silicone disc to be heated are placed. Two magnetic discs, one above the coils and the other under the wafer, may be used in order to improve the device performance (increase the power uniformity and the level of absorbed power). The eddy currents occur in all the conductive regions: graphite, wafer,

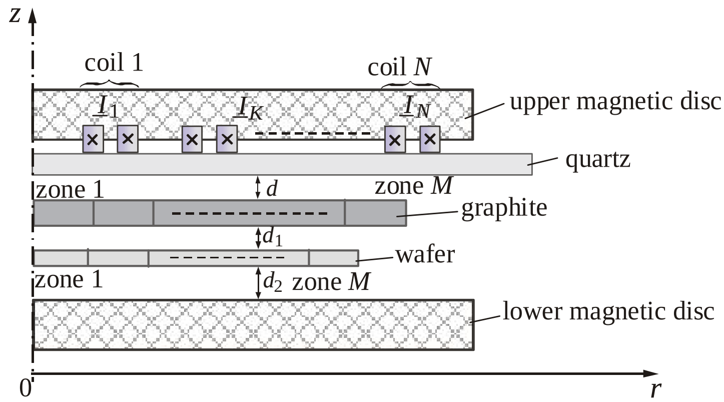

Fig. 1 – Zone-control induction heating applicator.

magnetic discs and exciting coils. The magnetic field satisfies the vector differential eq. with partial derivatives written in complex form

$$\mathrm{rot}\left(\frac{1}{\mu}\mathrm{rot}\underline{\mathbf{A}}\right)+\left(\mathrm{j}\omega\sigma-\omega^2\varepsilon_0\varepsilon_\mathrm{r}\right)\underline{\mathbf{A}}=\underline{\mathbf{J}}^{(e)}, \tag{1}$$

where $\underline{\mathbf{A}} = \underline{A}_\theta\mathbf{e}_\theta$ is the complex magnetic vector potential and $\underline{\mathbf{J}}^{(e)}$ – the density of the externally applied current in the coils. In this study the materials are considered to be linear and non-parametric. The power dissipated in the k^{th} zone of the graphite or of the wafer can be determined with the relation

$$P_{D_k}=\iint_{D_k}\underline{\mathbf{J}}\underline{\mathbf{E}}^*2\pi r\,\mathrm{d}r\,\mathrm{d}z,\quad (k=1,\ldots,M), \tag{2}$$

where D stands for the domain,

$$D=\begin{cases} w, \text{wafer domain,} \\ g, \text{graphite domain.}\end{cases}$$

The number of monitored zones, M, can be equal or larger than the number of coils, N.

Since the volumes of the monitored zones are not equal, the mean power dissipated in each region, defined as

$$Q^{(D)}_{\mathrm{av\_mean}_k} = \frac{P_{D_k}}{V_k} = \frac{\iint\limits_{D_k} p_v(r,z) 2\pi r \,\mathrm{d}r\,\mathrm{d}z}{\iint\limits_{D_k} 2\pi r\,\mathrm{d}r\,\mathrm{d}z}, \ (k = \overline{1, M}), \tag{3}$$

is used for evaluating the heating non-uniformity factor

$$F_D = \frac{\max\limits_k \left(Q^{(D)}_{\mathrm{av\_mean}_k} \right)}{\min\limits_k \left(Q^{(D)}_{\mathrm{av\_mean}_k} \right)}, \ (k = \overline{1, M}). \tag{4}$$

The best value for F_D is, evidently, $F_D = 1$, *i.e.* a minimum of F_D is sought.

The total powers dissipated in the wafer and in the graphite are also important for the reduction of the heating time,

$$P_D = \sum_{k=1}^{M} P_{D_k}, \tag{5}$$

where D is the wafer or graphite domain. P_D is to be maximized.

3. Preliminary Study

A preliminary study of the device presented in Fig.1 in the case $N = M = 12$ (12 zones and 12 coils) was firstly conducted in order to asses the influence of the current frequency and that of the upper and lower magnetic cores on the level of power uniformity and on the total absorbed power in the wafer and graphite. The case of equal current amplitudes in all the coils, $I_k = 150$ A, and a distance $d = 1.5$ mm, was firstly analysed. Two sets of values for the wafer and graphite conductivity, corresponding to the case of the material cut in parallel to the crystal basal plane or to a cut perpendicular to the basal plane, and a standard wafer of 300 mm in diameter and 0.775 mm in height were considered. The material constants are summarized in Table 1.

Table 1

Material Properties

	Graphite		Wafer		Quartz	Coils	Magnetic core	Air
	|| basal	⊥ basal	|| basal	⊥ basal				
Conductivity S/m	112,360	3,000	9,090	1,000	10^{-12}	5.99e7	0.025	0
Relative permittivity	1		10		4.2	1	1	1
Relative permeability	1		1		1	1	32	1

The magnetic field problem was analysed using the COMSOL Multiphysics software and the MATLAB interface. Fig. 2 plots the total powers, P_w and P_g , *versus* frequency, for the case with both magnetic, or with only the upper one, and the larger conductivities of the wafer and graphite.

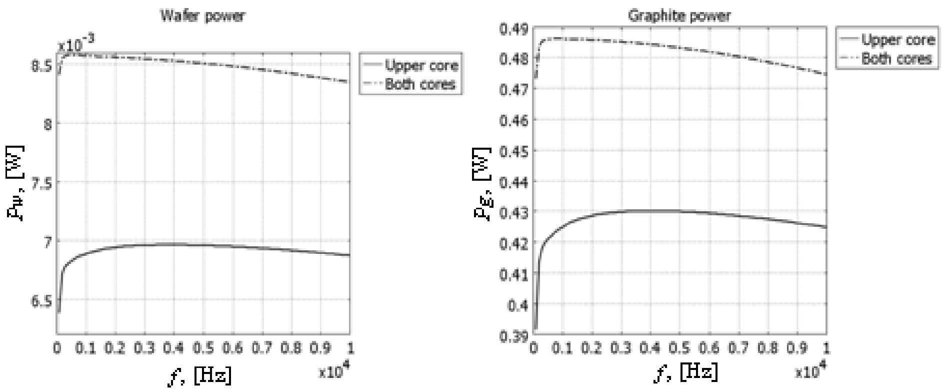

Fig. 2 – Dissipated power *versus* frequency for the case of one or two magnetic cores.

The results obtained in this preliminary investigation lead to the following conclusions:

a) the simultaneous presence of both magnetic cores has a positive influence on the power uniformity throughout the wafer and graphite plates and also on the total absorbed powers (both objective functions, F_D and P_D , are improved); the obtained results with two magnetic cores are better than those with only the upper core, which are in turn better than those obtained when no magnetic cores are used;

b) the non-uniformity factor, F_D, decreases for increasing frequencies;

c) there is a frequency for which the powers P_w and P_g are maximum, both in the case of one or two magnetic cores;

d) the decrease in the distance d_2 between the lower magnetic core and the wafer decreases the power non-uniformity and leads to a small power increase (improves both objective functions);

e) the total observed powers are much larger in the case of silicon and graphite cut parallel to the basal plane in all cases, due to their larger conductivities.

The values of the mean power dissipated in each zone of the wafer and graphite, when both cores are used, are plotted in Figs. 3 and 4 for d = 1.5 mm, d_2 = 6 mm, f = 200 kHz and f = 40 kHz, respectively. Besides illustrating the previous conclusions, these plots show that the largest difference in the mean absorbed powers appears between zone 1 and zone 12, while P_{k_mean} has a relatively small variation for k = 3,…,12 (for f = 40 kHz and below). This observation suggests that, besides the general case when all current amplitudes are independent variables, a simple solution that can be firstly tried to test the improvement in the non-uniformity factor, F_D, is to consider all currents in the outer coils equal to $I_k = \mathrm{coeff} \cdot I_1,\ k = \overline{2,N},\ \mathrm{coeff} \in [0,\ 1]$.

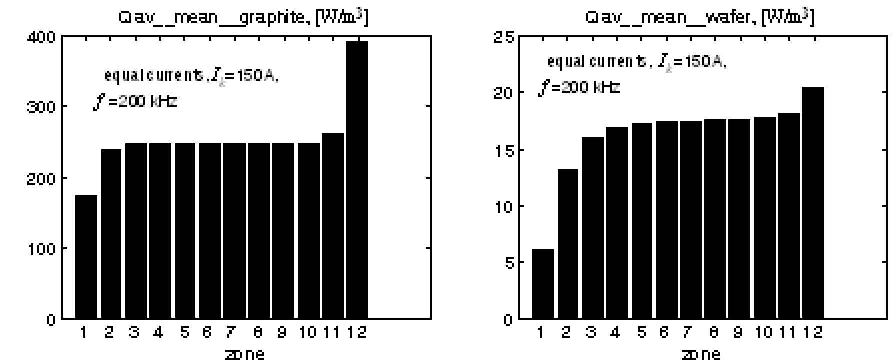

Fig. 3 –Mean dissipated power per zones in the graphite and wafer for f = 200 kHz and equal currents in all coils.

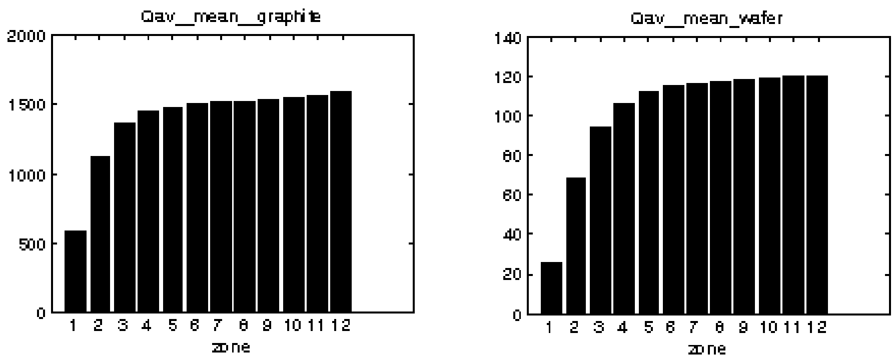

Fig. 4 –Mean dissipated power per zones in the graphite and wafer for f = 40 kHz and equal currents in all coils.

4. Optimization of Current Amplitude

A mono-objective optimization problem, the minimization of F_w, was firstly addressed using the evolutionary strategy SE(1,λ), one parent, λ descendants, considering as independent variables the ratios I_k/I_1, ($k = \overline{2,N}$), (Dumitrescu, 2000). Several cases were analysed (f = 4 kHz, f = 40 kHz, d_2 = = 6 mm, N = 12, d = 1.5 mm), with an initial point for the stochastic search either prescribed or randomly generated. A number of λ = 5 descendants was used, but the cases λ = 3 and λ = 7 were also tested. The convergence was slow and sometimes no improvement in the objective function was obtained after 20 generations. This fact may be attributed both to the large number of design variables (N – 1 = 11) and large search space ($I_k/I_1 \in [0, 1]$). A minimum value of F_w = 1.41 was obtained for the vector of design variables [0.29, 0.68, 0.54, 0.41, 0.67, 0.64, 0.76, 0.56, 0.45, 0.66, 0.18].

This slow convergence, leading to rather poor results, induced the idea to try the optimization in the case of only one design variable (c o e f f), using the simple version of the Hooke and Jeeves direct search method, that implies the search is performed in only one direction at a certain time (Bianchi *et al.*, 1995; Boţan, 2007). If the results in this case prove satisfactory from the point of view of power uniformity, then this is, of course, a much suitable solution from practical considerations, since the currents in all the outer coils are equal (one variable to control).

Table 2 presents the results obtained using a direct search method in order to find the value of the ratio I_k / I_1 , ($k = \overline{2, N}$), that renders a minimum of F_w. The values of F_g, P_w and P_g are also displayed. The results correspond to N = M =12 and to a distance d=1.5 mm between the graphite and the quartz plates. The direct search method proves to be much less time consuming than the evolutionary strategy ES(1, λ) and leads to acceptable values for the power non-uniformity in the wafer and graphite, but rather poor values for the total absorbed powers, P_w and P_g.

Table 2

Influence of Magnetic Cores and Frequency over Power Uniformity and Total Power

Cores	f kHz	d_2 mm	c o e f f	F_w	F_g	P_w mW	P_g mW
Upper and lower	4	2	0.3	1.24	2.01	0.78	44
		6	0.26	1.24	2.39	0.57	33
	40	2	0.36	1.23	1.97	0.84	48
		6	0.3	1.20	2.51	0.58	33
	200	2	0.55	1.18	2.02	0.29	20
		6	0.45	1.21	2.88	0.20	13
Upper	4	–	0.23	1.27	3.20	0.37	23
	40	–	0.29	1.26	2.83	0.46	29
	200	–	0.4	1.29	3.58	0.14	10
No cores	4	–	0.23	1.28	3.20	0.38	24
	40	–	0.27	1.26	3.16	0.41	26
	200	–	0.4	1.32	3.53	0.15	11

In an attempt to improve the objective function values, the case when the quartz plate and the graphite plate are in direct contact (d = 0) is further analysed, all the other distances being unchanged. Figs. 5 and 6 plot the frequency dependence of the power non-uniformity and the total absorbed power, respectively, in the wafer and in the graphite, for the configurations with both magnetic discs, with only the upper magnetic disc, or with no magnetic discs. The results correspond to the value of the design variable c o e f f that renders the minimum value of F_w for the analysed frequency and configuration, and to $N = M = 12$.

As may be seen, the best values of both objective functions are obtained when both magnetic discs are used. Figs. 5 and 6 also suggest that if only one control variable is used (c o e f f), the indicated working frequency is below 50 kHz, since larger power levels are attained. If the customary frequency $f =$ $= 40$ kHz is employed then the power non-uniformity may be reduced to 1.18 in the wafer and to 2.07 in the graphite region.

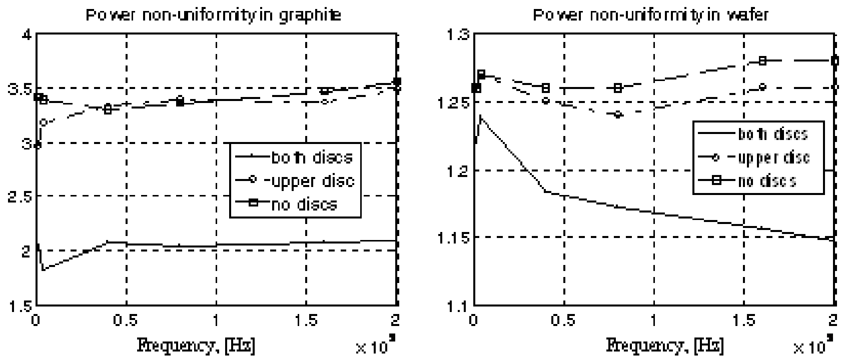

Fig. 5 – Influence of magnetic discs and frequency over the power non-uniformity.

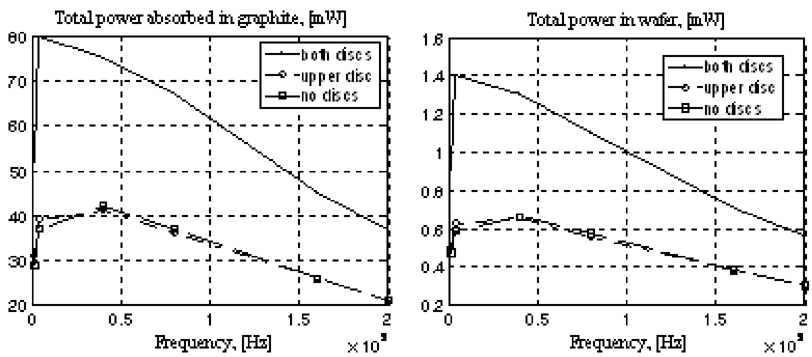

Fig. 6 – Influence of magnetic discs and frequency over the total absorbed powers.

In an attempt to simplify the structure of the induction heating device, the case when only $N = 8$ coils are used was also analyzed for the configuration with two magnetic discs.

Fig. 7 presents a synthesis of the obtained results when using $N = 8$ and $N = 12$ coils, respectively, and power monitoring is done for $M = 12$ zones (in the case when improved values of F_D and P_D are obtained, d = 0, d_2 = 2 mm). The results correspond to the optimized value of the control variable c o e f f. These results show the better performance in terms of both F_D and P_D for the configuration with 12 coils, this effect being more evident for frequencies larger than 50 kHz. It may be also noted that for f = 40 kHz the values of F_w, F_g, P_w and P_g are nearly the same in both cases (N = 8 and N = 12 coils) for the optimized value of c o e f f. Thus, in this case, f = 40 kHz, the device configuration can be indeed simplified by using only 8 coils with two wires each. The working frequency, f = 4 kHz, is also of interest since it renders the largest power levels and the smallest heat non-uniformities for the optimized value of c o e f f (c o e f f = 0.4) in the case when 12 coils are used.

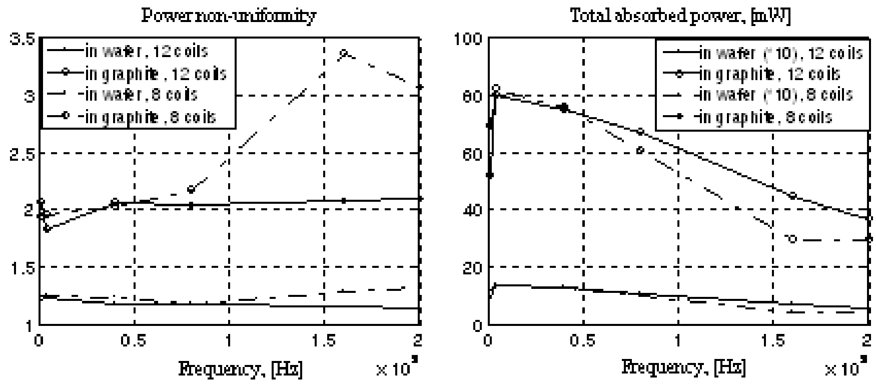

Fig. 7 – Power non-uniformity and total absorbed powers for N = 8 coils and N = 12 coils, M = 12 monitored zones.

4. Conclusions

The induction heating device for heating silicone wafers was modified and analysed for improved performance in terms of heating uniformity and total absorbed power. The solution of using two magnetic cores close to the coils and wafer improves both objective functions. A simple control scheme, in which the current amplitudes in the outer coils are all equal to the same fraction of that in the innermost coil, and a suitable choice of working frequency significantly reduce the power non-uniformities. The direct search method proved to be more satisfactory in terms of CPU time than ES(1, λ). The obtained results show that by using only one control variable and two magnetic cores the power non-uniformity in the wafer can be reduced to 1.183 for a working frequency of 40 kHz.

Starting from the results obtained in this paper our future studies intend to determine an optimal configuration of this multi-objective optimization problem using other evolutionary algorithms and direct search methods and more design variables.

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ÎMBUNĂTĂȚIREA PERFORMANȚELOR UNUI SISTEM BAZAT PE CONTROLUL ZONAL DESTINAT ÎNCĂLZIRII INDUCTIVE A UNOR DISCURI CIRCULARE SEMICONDUCTOARE

(Rezumat)

Se propune o îmbunătățire a dispozitivului de încălzire inductivă cu control zonal destinat procesării unor discuri semiconductoare subțiri, prin utilizarea a două discuri magnetice cu rol de ecran şi a unui sistem de 12 bobine ce se extind în direcție radială (direcția în care neuniformitatea densității puterii disipate este maximă). Se urmăreşte minimizarea factorului de neuniformitate a puterii disipate în discul semiconductor şi maximizarea puterii totale disisipate în acesta. Se constată că, pentru configurația cu discuri magnetice, utilizarea unei variante simplificate a controlului zonal, în care curenții din toate bobinele exterioare reprezintă aceeaşi fracție din curentul din bobina interioară, conduce la rezultate satisfăcătoare în ceea ce priveşte ambele funcții obiectiv.