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DESIGN OF INDUCTION HEATING DEVICE OPTIMIZED FOR TEMPERATURE UNIFORMITY IN SEMICONDUCTOR WAFER USING EVOLUTIONARY STRATEGIES

BY

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Abstract. An optimization of a zone controlled induction heating device using the evolutionary strategies is presented. The design variables are the frequency, the amplitude and initial phase of the currents in the induction coils. Optimization is carried out based on a newly defined objective function as well as, for comparison, on an objective function presented in literature.

Key words: induction heating; uniform temperature; evolutionary strategies.

1. Introduction

In the industrial process of manufacturing photovoltaic cells a heating stage of the semiconductor wafer that hosts the cells is involved. From the various heating methods (inductance heating, resistance heating, lamp heating), induction heating is preferred due to the high speed of the process and the high temperatures that can be attained (up to 2,000ºC).

High temperature heating of a semiconductor wafer substrate is also used in the epitaxial growth process, a key stage in the fabrication of electronic devices. An important demand during the heating of a semiconductor wafer is

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temperature uniformity. This can be attained only through a careful design and a proper mode of excitation of the induction coils that render a quasi-uniform power dissipation in the wafer.

Okamoto *et al*. (2004) have studied a transverse flux induction heating device and the concept of zone control, which consists in monitoring the dissipated power in a number of subdomains (“zones”) in an auxiliary graphite plate that radiates heat to the wafer, is introduced.

The idea is further developed by Miyagi *et al*. (2006); in this case the effect of increasing the number of zones and that of changing the frequency in one of the coils, being investigated.

The present paper addresses the study of the device proposed by Okamoto *et al*. (2004) considering some other design variables, such as the frequency in all the coils and the coil section shape (rectangular or square). In each case the quasi-optimal configuration is obtained using evolutionary strategies (ES). This evolutionary technique, introduced by Rechenberg (1973) and Schwefel (1981), was later on increasingly studied and used in optimization problems due to its simplicity (the use of smaller population sizes and, in most cases, only one genetic operator – mutation) (Dumitrescu, 2000; Ferariu, 2004). In our previous papers (Ferariu *et al*., 2007; Petrescu, 2006), the optimal configuration of some electromagnetic devices was sought using ES.

The paper is organized in five sections. Section **2** presents the induction heating device and sets the eqs., the design variable space and the objective space for the problem. Section **3** outlines the features of the implemented ES, while section **4** presents and discusses the obtained results. Finally, some conclusions are emphasized in section **5**.

2. Problem Formulation

A simplified model of the transverse-flux induction heating equipment using “zone control” is presented in Fig.1. The device has axial symmetry and can be analysed in the (r, z) plane. The induction coils, each containing two wires, are set on an insulating quartz plate, underneath which a graphite plate is placed. The silicon wafer is set beneath the graphite plate, at a small distance. The coils are supplied with sinusoidal currents having equal frequencies, f, in the RF range, but different amplitudes, I_1,..., I_8. Heating of the graphite and wafer occurs due to the induced eddy currents.

The magnetic field problem can be analysed in terms of the total magnetic vector potential, $\underline{\mathbf{A}}$, which satisfies the differential eq. with partial derivatives (d.e.p.d) written in complex form

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

where σ, ε_r and μ represent the material electric and magnetic constants, $\omega = 2\pi f$ – the angular frequency and $\underline{\mathbf{J}}^{(e)}$ – the externally applied current density (non-zero in the coils, zero elsewhere).

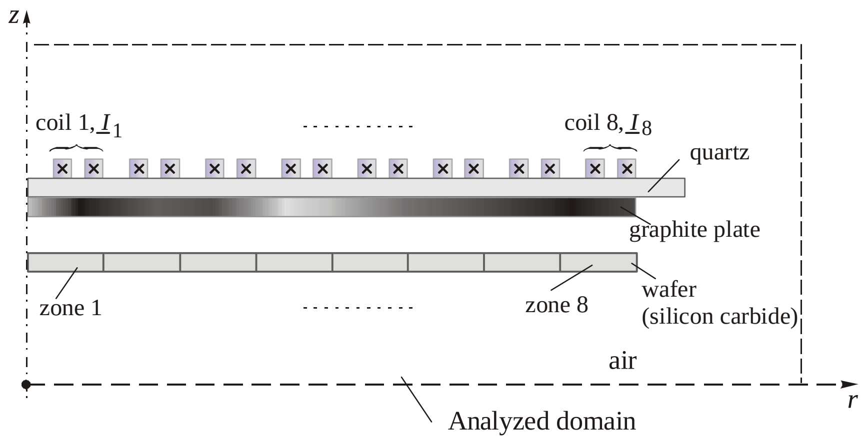

Fig. 1

The stationary, linear, uncoupled problem, which considers the material properties constant, not depending on the magnetic field and on temperature, is considered. The magnetic field problem can be conveniently analysed in COMSOL Multiphysics, using the AC/DC, quasistatics magnetic, azimuthal induction currents module. Unlike the procedure described by Okamoto *et al*. (2004) and Miyagi *et al*. (2006), where the zone control technique was applied to the graphite plate, in this paper the wafer was considered to be divided in 8 regions, D_i , in which the dissipated power produced by the eddy currents in each region, *i*

$$P_i = \iint_{D_i} \underline{\mathbf{J}}\underline{\mathbf{E}}^* \cdot 2\pi r \,\mathrm{d}r\,\mathrm{d}z\,, \ \ (i = 1,...,8), \tag{2}$$

was monitored. This decision was taken because heating uniformity is paramount in the wafer region.

Since the goal of the optimization process is to obtain a uniform heating in the wafer, a suitable choice for the objective function can be (Okamoto *et al*., 2004)

$$F = \frac{\max\limits_i \left(P_i\right)}{\min\limits_i \left(P_i\right)}, \ \ (i = 1,...,8)\,. \tag{3}$$

However, since the domains D_i have increasing volumes, but equal radial expansion, Vol(D_1)< Vol(D_2)<…< Vol(D_8), the objective function defined by (3) is not altogether accurate in describing the power uniformity (integration is done on larger volumes as i increases, so that although the power density on domains at the wafer periphery might be small, the powers P_i could result with close values). That is why an amended objective function is proposed in this paper namely

$$F^{(1)} = \frac{\max\limits_i \left(P_{i\_\text{mean}}\right)}{\min\limits_i \left(P_{i\_\text{mean}}\right)}, \quad P_{i\_\text{mean}} = \frac{P_i}{V_i}, \quad (i = 1,...,8), \tag{4}$$

where V_i is the volume of region i.

The stochastic search aims to find the minimum of $F^{(1)}$

$$F_{\text{best}}^{(1)} = \min_x \left(F^{(1)}(x)\right), \tag{5}$$

where $x \in S \subset \mathbb{R}^n$ is the vector of n design variables with real values and S – the search space. However, there may be other objective functions which reflect the uniformity of heating such as

$$F^{(2)}\Big|_D = \frac{\max p_v(r,z) - \min p_v(r,z)}{\text{mean}\, p_v(r,z)}\Bigg|_D, \quad (r,z) \in D,\ D = \bigcup_{i=1}^{8} D_i, \tag{6}$$

which calculates the difference between the maximum and minimum power density, $p_v(r,z) = \underline{\mathbf{J}}\, \underline{\mathbf{E}}^*$, divided by the mean power density

$$\text{mean}\, p_v(r,z) = \frac{\int_D p_v(r,z)\, 2\pi r\, \mathrm{d}r\, \mathrm{d}z}{\int_D 2\pi r\, \mathrm{d}r\, \mathrm{d}z}, \tag{7}$$

in the whole wafer $D = \bigcup_{i=1}^{8} D_i$, or the set

$$F^{(3)} = \left\{ F^{(2)}\Big|_{D_1}, ..., F^{(2)}\Big|_{D_8} \right\}, \tag{8}$$

where $F^{(2)}\Big|_{D_i}$ is calculated with (6) on the subdomain D_i. In both cases minimization of the objective function is sought.

The design variables were considered to be the amplitude and phase of the sinusoidal currents in the coils and their frequency. Fixed coil radii were considered in this study, but the influence of the wire section shape, square or rectangular, was investigated.

3. Evolutionary Strategy Implementation

Evolutionary strategies were conceived for optimization problems with continuous design parameters. The decision variables have real representations and the stochastic search in the design variable space is performed by random mutations using the standard normal Gaussian distribution.

In its simplest implementation, ES(1+1), the parent and offspring populations contain, each, one individual (one parent produces one offspring) using the evolution law

$$x^{(o)} = x^{(p)} + N(0,\sigma)\,, \tag{9}$$

where $x^{(o)}$ and $x^{(p)}$ are n-dimensional vectors containing the design parameters and $N(0,\sigma)$ – an n valued vector containing the perturbation, *i.e.* random numbers with normal distribution and dispersion, σ.

In more advanced implementations the parent and offspring populations have $\mu > 1$ and $\lambda > \mu$ individuals, respectively. The selection of the fittest individuals is deterministic and elitist and favours the best μ individuals (in a minimization problem those with the smallest objective function values). Selection of the parent population for the next generation can be done in the offspring population, the so called ES(μ, λ) strategy, or it can be done in the whole parent and offspring population containing μ + λ individuals, the so called *ES*(μ + λ). In this paper the ES(1 + 1) and ES(1, λ) were used.

One way to modify the control parameter of the ES, the dispersion σ, is by using the deterministic "1/5 rule" (Dumitrescu, 2000), as described by the eq.

$$\sigma^{t+1} = \begin{cases} c\,\sigma^t \text{ , if } \varphi(N) < 1/5; \\ \sigma^t \text{ , if } \varphi(N) = 1/5; \\ c^{-1}\sigma^t \text{ , if } \varphi(N) > 1/5. \end{cases} \tag{10}$$

In (10) σ^t and σ^{t+1} represent the dispersion used for generating the offspring population at generations t+1 and t, respectively, $\varphi(N)$ represents the probability of success in the last N generations,

$$\varphi(N) = \frac{\text{number\_of\_successfulmutations}}{N} \tag{11}$$

and c is a constant situated in the range [0.82, 0.85], (Dumitrescu, 2000). The number N is usually set to be 10 times the number of design variables.

Another approach is to encode the dispersions, which have different values for each decision variable, in the representation of the individuals. Thus an individual is a vector of the form (Ferariu *et al.*, 2007)

$$a = (x, \sigma), \tag{12}$$

where: $x = [x_i]_{i=1,n}$ specifies the decision parameters and $\sigma = [\sigma_i]_{i=1,n}$ denotes the standard deviations for the Gaussian mutation. During the evolutionary process both the dispersions and the design variables are subject to mutations following the rules

$$\begin{aligned} \sigma_i^{(o)} &= \sigma_i^{(p)} \exp\left[\tau N(0,1) + \tau_1 N_i(0,1)\right], \\ x_i^{(o)} &= x_i^{(p)} + N_i(0, \sigma_i^{(o)}), \ \ (i = 1,...,n), \end{aligned} \tag{13}$$

where the indexes *o* and *p* refer to an offspring or parent, respectively. Mutation is first applied to the dispersion, σ. The constants τ and τ_1 have the expressions $\tau = 1/\sqrt{2n}$, $\tau_1 = 1/\sqrt{2\sqrt{n}}$, (Dumitrescu, 2000).

In the case of the ES(μ, λ), and ES(μ + λ) strategies $x^{(o)}$ and $x^{(p)}$ are data arrays with the dimensions λ × *n* (for $x^{(o)}$) and μ × *n* (for $x^{(p)}$), each line containing the *n* design parameters of an individual.

4. Results and Discussions

The mono-objective optimization problem was dealt with using procedures implementing ES(1+1) and ES(1, λ) written in MATLAB. The *m*-file for the objective function evaluation was generated using COMSOL Multiphysics 3.5.a which creates the FEM structure for the analysis of the induction heating system presented in Fig. 1. The case of heating a wafer of 300 mm in diameter and 1 mm thickness was considered. The properties of the various subdomains are summarized in Table 1.

Table 1

	Graphite	Wafer	Quartz	Coils	Air
Conductivity, [S/m]	3,000	1,000	1e-12	5.998×10^7	0
Permittivity	1	10	4.2	1	1
External current density, [A/m^2]	0	0	0	2×10^6	0
Relative permeability	1	1	1	1	1

The design variables vector was in turn considered to be:

a) $x = \left[|\underline{I}_2|, |\underline{I}_3|, ..., |\underline{I}_8| \right]$;

b) $x = \left[|\underline{I}_2|, |\underline{I}_3|, ..., |\underline{I}_8|, f \right]$;

c) $x=\left[\left|\underline{I}_2\right|,\left|\underline{I}_3\right|,...,\left|\underline{I}_8\right|,\ \arg\left\{\underline{I}_2\right\},...,\ \arg\left\{\underline{I}_8\right\},f\ \right]$,

where $\arg\left\{\underline{I}_k\right\}$, $(k=\overline{2,8})$, denotes the initial phase of the current in the k-th coil. The current in coil 1 was considered to be fixed and the ratio $\left|\underline{I}_k\right|/\left|\underline{I}_1\right|$, $(k=\overline{2,8})$, and the initial phase were modified during the stochastic search.

The search space, S, for the design variables, is presented in Table 2.

Table 2

	$\left\|\underline{I}_k\right\|/\left\|\underline{I}_1\right\|$	$\arg\left\{\underline{I}_k\right\}$	f, [kHz]
min	0	$-\pi$	20
max	2	π	50

In the initial simulations a fixed start point for the search was used. Considering all the design variables (case c) this was x = [1, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0, 0, 0, 0, 0, 0, 0, 4×10^4] which gives an initial value of the objective function F = 18.87 (for the rectangular wire cross-section). Since the induced electric field produced by one coil has minimum values on the axis r = 0 and increases for increasing r, the influence of imposing the restriction condition

$$\left|\underline{I}_k\right|>\left|\underline{I}_{k+1}\right|,\ (k=\overline{1,7}), \tag{14}$$

was tested. Table 3 summarizes the results obtained in the numerical simulations using the evolutionary strategies for the minimization of the objective function (3).

Table 3

Strategy	Case	Restrictions	Wire cross-section	Best obj fcn. value
ES(1+1)	a)	$x \in S$	rectangular	12.1
ES(1+1)	a)	$x \in S$ & rel. (14)	rectangular	3.2
ES(1+1)	b)	$x \in S$ & rel. (14)	rectangular	2.1
ES(1+1)	c)	$x \in S$ & rel. (14)	rectangular	4.2
ES(1, λ)	b)	$x \in S$ & rel. (14)	rectangular	1.9
ES(1, λ)	c)	$x \in S$ & rel. (14)	rectangular	2.1
ES(1, λ)	b)	$x \in S$ & rel. (14)	square	2.1

The data in Table 3 show that convergence in case c), when the initial phase is among the design variables, is very slow; on the contrary in cases a) and b), when only the current amplitude and frequency are independent variables, a faster convergence is attained, the best result of the minimization, F = 1.9, being obtained with the strategy ES(1, λ) for a rectangular wire cross-section.

Since the results obtained using a fixed start point didn't prove satisfactory, the subsequent simulations used a start point for the design variable generated randomly in the search space using the rule

$$x_i\big|_{\mathrm{gen\_0}} = \mathrm{lim\_inf}\ (x_i) + \left[\mathrm{lim\_sup}\ (x_i) - \mathrm{lim\_inf}\ (x_i)\right]\mathrm{rand}(1), \qquad (15)$$

where lim_inf and lim_sup represent the lower and upper bound for x_i and rand(1) is a uniformly distributed random variable in the range [0, 1]. Both the deterministic "1/5 rule" and the stochastic exponential rule, defined by $(13)_1$ were used. The best results obtained with ES(1, λ) for the amended objective function (4) are presented in Table 4.

Table 4

Case	Restrictions	Self adaptation algorithm	Best obj. fcn. value
a)	$x \in S$	1/5 rule	4.47
b)	$x \in S$	eq. $(13)_1$	1.39
a)	$x \in S$	eq. $(13)_1$	1.08

As may be seen, usage of the stochastic auto-adaptation algorithm for the control parameters of ES(1, λ), together with the random generation of the initial point for the search, clearly lead to a solution close to the theoretical best, $F^{(1)}\big|_{\mathrm{best}} = 1$. As in the previously analysed case (fixed start point and "1/5 rule"), usage of a larger number of design variables leads to a slower convergence.

5. Conclusions

The optimization of an induction heating system, used in semiconductor and photovoltaic cell processing, which aims to find the frequency and the current distribution in the exciting coils for uniform semiconductor heating, is treated using simple evolutionary strategies. An amended objective function for the temperature uniformity optimization in the wafer zones is proposed. The study proves the clear advantage of using a random choice for the initial point in the evolutionary search and that of using a stochastic, exponential algorithm for the self-adaptation of the dispersion, σ.

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PROIECTAREA UNUI DISPOZITIV DE ÎNCĂLZIRE PRIN INDUCȚIE PENTRU A OBȚINE O TEMPERATURĂ UNIFORMĂ UTILIZÂND STRATEGII EVOLUTIVE

(Rezumat)

Se propune o optimizare bazată pe strategii evolutive a unui dispozitiv de încălzire prin inducție electromagnetică. Variabilele de proiectare sunt frecvența, amplitudinea şi faza inițială a curenților din bobinele inductoare. Optimizarea vizează o funcție obiectiv definită în lucrare privind uniformitatea încălzirii, precum şi, pentru comparație, o funcție obiectiv preluată din literatură.