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Analysis of Multi Coil Induction Heating System for Semiconductor Processing

Nisha[1], Vishwas K[2], Suryanarayana K[3], Rajaneesh Acharya[4]

PG Scholar, E&E department, NMAM Institute of Technology, Karkala, India [1]

Design Engineer, HEXMOTO Controls Pvt. Ltd., Mysore, India[2]

Associate Professor, E&E department, NMAM Institute of Technology, Karkala, India[3,4]

Abstract: Heating by induction is a promising technology for processing circular semiconductor wafers because it offers quick and high temperature heating. Heat develops inside the work piece hence losses due to conduction and radiation is reduced. It is rather difficult to attain uniform temperature distribution in the work piece using single coil induction heating method. In this paper, a multi coil induction heating system for processing circular semiconductor wafers is proposed. The working coil or inductor is divided into a number of multi turn coils. The paper presents ANSYS Maxwell 3D modelling and simulations of the four coil induction heating system. The phase angle between the currents differs by 90º to generate a travelling wave magnetic field that can uniformly heat the subsector.

Keywords: Induction heating, semiconductor processing, uniform heating, travelling wave

I. INTRODUCTION

Several phases of semiconductor processing technology need high temperature heating of the wafer. In Vapour Phase Epitaxy(VPE) the single crystal SiC wafer has to be heated to a high temperature of 1450–1700ºC [1]. Conventionally the semiconductor wafers are heated inside a halogen lamp Rapid Thermal Processing (RTP) chambers which uses surface absorption method to heat the wafer. The presence of thick oxide layer makes it difficult to rapidly heat the wafer [2].Induction heating method is preferred for semiconductor processing as this method has the advantages of quick and high temperature heating. In induction heating there is no physical contact between the inductor and work piece and heat develops inside the work piece [3].

A high uniformity in temperature distribution across the wafer is desired to avoid any stress resulting from expansion of the semiconductor wafer due to uneven heating. In case of single coil induction heating system it is difficult to attain uniform heat distribution in the work piece. Several methods that use single and split working coils to control the heat distribution in the work piece have been proposed. A multi zone induction heating system has been proposed that uses multiple split working coils each associated with a particular zone of the work piece. A single inverter is used to control the currents in each working coils via switching gears [4]. In [5] a single inverter multi load topology is proposed. It uses two working coils each connected to a resonant capacitor, operating at different resonance frequency. The inverter is connected to one of the loads based on the selected resonant frequency. Authors in [6,7,15] have proposed a zone control induction heating method (as shown in Fig. 1) in which the working coil is divided into several split coils each controlling the particular zone of the work piece. All the inverter currents are maintained at the same frequency to reduce amplitude variations. The inverters provide phase angle control by making each coil current in phase with others. This reduces the active power circulation between the inverters, thereby providing uniform heating of the work piece even in the presence of mutual inductance between the split working coils. The problem with ZCIH method is that the current in a coil effects the heat distribution in not only that zone but also the neighbouring zones.

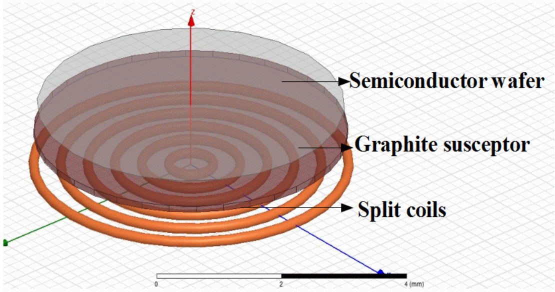

Fig.1 Six zone control induction heating system

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Several improvements to the ZCIH have been proposed in the literature to achieve better power control and heat distribution in the work piece. In [7] the Finite Element results show that better uniformity can be achieved by controlling both current and frequency. In [8, 9] phase angle control of coil currents under both steady state and transient conditions is proposed. This method reduces the circulating power between the inverters and offers wide range of control of heat generated by the working coils. In another approach real and imaginary components of the current in the coil are detected and controlled instead of controlling amplitude and phase of the coil currents. The use buck converters to regulate the dc ink voltage to the inverter is eliminated and decoupling control for the coil currents eliminates the use of decoupling transformers for the coils and system stability is improved[10,11]. A 3D resistance matrix to analyse the relation between currents and heat distribution is proposed [12, 13, and 14]. In this paper a four coil induction heating system is proposed and simulated using ANSYS Maxwell 3D FEA tool. In sub section A and B the mathematical modelling for the induction heating system is given. In section II and III 3D modeling and simulations of the proposed four coil induction heating system that uses travelling wave magnetic field to induce eddy currents in the graphite suspecter is given.

A. Equations governing induction heating process

Maxwell equations are the governing equations for the basic induction heating phenomenon. For time varying magnetic fields the Maxwell equations in differential form is given by,

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad (1)$$

In most of the induction heating process excitation frequency is below 10MHz at which conduction current density is much higher than the displacement current density,

$$\nabla \times \vec{H} = \vec{J} \quad (2)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (3)$$

$$\nabla \cdot \vec{B} = 0 \quad (4)$$

$$\nabla \cdot \vec{D} = \rho \quad (5)$$

Where,

$\vec{E}$ – Electric field intensity (V/m)
$\vec{H}$ – Magnetic field intensity (A/m)
$\vec{D} = \varepsilon\vec{E}$– Electric flux density
ρ – Specific resistance
σ – Electric conductivity
μ- Magnetic permeability

The relation between magnetic flux density and magnetic field intensity is,

$$\vec{B} = \mu\vec{H} \quad (6)$$

The ohms law in point form is given by,

$$\vec{J} = \sigma\vec{E} \quad (7)$$

As the magnetic flux density **B** satisfies a zero divergence, the magnetic vector potential **A** can be introduced.

$$\vec{B} = \nabla \times \vec{A} \quad (8)$$

From equations (3) and (8),

$$\nabla \times \vec{E} = -\nabla \times \frac{\partial \vec{A}}{\partial t} \quad (9)$$

Integrating (9) results in,

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - \nabla\varphi \quad (20)$$

From equations (2) and (7),

$$\nabla \times \vec{H} = \sigma\vec{E} \quad (31)$$

The equation governing induction heating can be derived using A-φ analytical method,

$$\vec{J} = -\sigma\left(\frac{\partial \vec{A}}{\partial t} + \nabla\frac{\partial \varphi}{\partial t}\right) + \vec{J_s} \quad (42)$$

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Equation 12 represents the induced eddy current density in the work piece generated by the time varying magnetic field due to time varying currents in the induction coil.
φ – Electric scalar potential
$\vec{J}s$ – Excitation current density (A/m^2)

B. Magnetic field produced by a single current carrying coil
The magnetic field at a point P(r,0,z) in the space due to alternating current flowing through a circular coil is determined by calculating the vector magnetic potential $\vec{A}$. Fig. 2 shows a circular coil of radius ‘a’, located at the origin. The coil is carrying time varying current I Ampere’s in the φ-direction. $\overrightarrow{dl}$is a differential length of the circular coil.

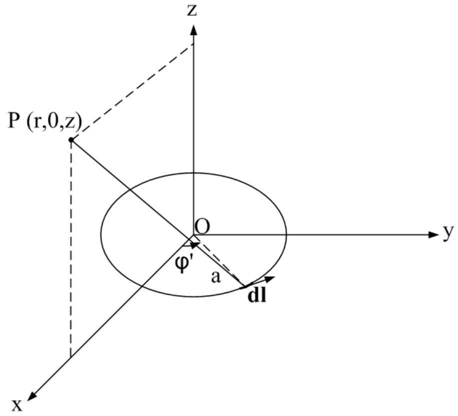

Fig.2 Circular coil carrying current I Ampere’s

The vector magnetic potential $\vec{A}$ at point P due to alternating current in the coil is given by,

$$\vec{A} = \left(\frac{\mu_0 I}{k\pi}\sqrt{\frac{a}{r}}E_1(k) - \frac{\mu_0 I}{k\pi}\sqrt{\frac{a}{r}}E_2(k) - \frac{\mu_0 Ik}{2\pi}\sqrt{\frac{a}{r}}E_1(k)\right)\hat{a}_\varphi \quad (13)$$

Where,

$k = \sqrt{\frac{4ar}{(r+a)^2+z^2}}$- Modulus of elliptic integral

$E_1(k) = \int_0^{\frac{\pi}{2}} \frac{d\theta}{\sqrt{1-k^2 \sin^2\theta}}$- Elliptic integral of first order

$E_2(k) = \int_0^{\frac{\pi}{2}} \sqrt{1-k^2 \sin^2\theta}\, d\theta$- Elliptical integral of second order

Magnetic field at point P can be found from $\vec{A}$ by using the relation,

$$\vec{B} = \nabla \times \vec{A}$$

$$\vec{B} = -\frac{\partial A_\varphi}{\partial z}\hat{a}_r + \frac{\partial A_\varphi}{\partial r}\hat{a}_z = B_r\hat{a}_r + B_z\hat{a}_z \quad (54)$$

Where,
The radial component of the magnetic field is given by,

$$B_r = \frac{\mu_0 I}{2\pi r\sqrt{z^2+(r+a)^2}}\left(\frac{a^2+z^2+r^2}{z^2+(r-a)^2}E_2(k) - E_1(k)\right) \quad (65)$$

The axial component of the magnetic field at point P is,

$$B_z = \frac{\mu_0 I}{2\pi\sqrt{z^2+(r+a)^2}}\left(\frac{a^2-z^2-r^2}{z^2+(r-a)^2}E_2(k) + E_1(k)\right) \quad (76)$$

II. PROPOSED FOUR COIL INDUCTION HEATING SYSTEM

ANSYS Maxwell 3D v15 software is used for finite element analysis of the multi coil induction heating system as shown in Fig.3. The graphite disc is used as the susceptor because of its good electrical conducting properties. The number of turns in the coils are selected so as achieve equal inductance in all the coils.

The phase angle of excitation current in the coils differs by 90º which results in a travelling wave magnetic field.

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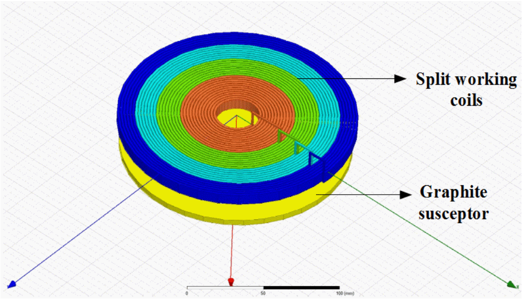

Fig.3 ANSYS Maxwell 3D model of the multi coil induction heating system

Travelling wave induction heating system mainly used for metal strip heating makes use of phase shifts between coil currents to generate a travelling wave magnetic field. Travelling wave induction heating system has advantages of single phase longitudinal flux heating, in addition to this properly designed travelling wave induction heating system uniformly heats the work piece. The concept of travelling wave arises from the fact that when the stator of an induction motor excited by three phase supply is linearly stretched, the rotating magnetic field in the air gap becomes a travelling wave magnetic field [16, 17].

The coils are excited by time varying currents that differ in phase by 90º. The phase sequence in the coils is listed in Table 1. The excitation current frequency is same in all the coils. By adjusting the current amplitudes in each coil heat distribution in the susceptor can be controlled. The semiconductor wafer is placed below the graphite susceptor to which heat is transferred by conduction. Table 2 shows the properties and dimensions of graphite disc used a susceptor.

TABLE I
EXCITATION CURRENTS IN THE COILS

Coil	**Number of turns**	**Excitation current (A)**	**Phase Angle (Deg.)**
Coil_1 (inner most)	12	40	0
Coil_2	8	40	90
Coil_3	7	40	180
Coil_4 (outer most)	6	40	270

TABLE III
GRAPHITE SUSCEPTOR PROPERTIES

Diameter	15cm.
Air gap between coils and susceptor	2cm.
Thickness	0.6cm.
Relative permeability	1
Bulk conductivity	70000Siemens /m

III. SYSTEM CONFIGURATION

The arrangement of circular graphite susceptor and working coils is shown in Fig. 4. The magnetic concentrators such as ferrite or fluxtrolcan be used so that the field does not interact with the metallic body of the system. The proposed multi coil induction heating system uses travelling wave magnetic field to induce eddy currents in the graphite susceptor and heat it by Joules' effect.

The power supply system uses four inverters for the four split working coils. The phase angle of each coil is controlled independently by the corresponding inverter. Fig. 5 shows the schematic of power supply to the four coil induction heating system is given.

The DC bus voltage is derived by rectifying a three phase 440V supply. The DC bus voltage is around 600VDC. A high frequency transformer will be used for each phase to boost up the current. Use of buck converters to control the dc link voltage of the inverters is eliminated.

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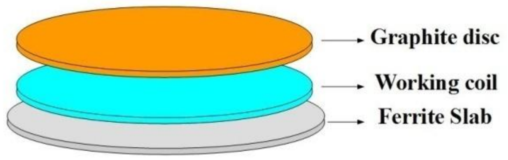

Fig.4 Arrangement of working coils and graphite susceptor

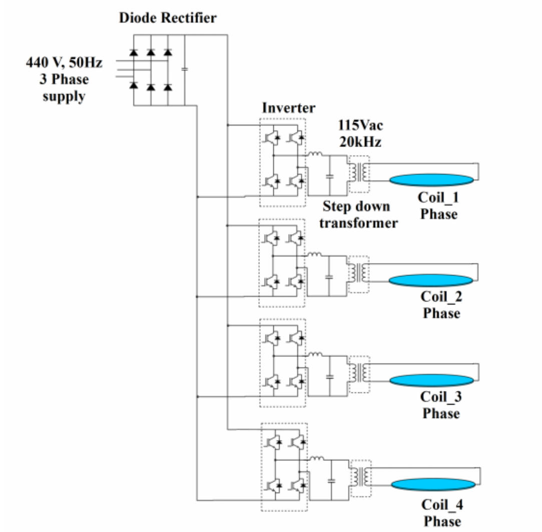

Fig.5 Block diagram of the supply system for four coil induction heating setup

IV. SIMULATION RESULTS

The ANSYS Maxwell 3D v15 FEA tool is used to model the four coil induction heating system. Eddy current solver is selected for analysing Ohmic loss distributions in the graphite susceptor. The flux density vector plot (Fig. 6) shows the travelling wave magnetic field generated by the differences phases of the coil currents. Fig. 7 and 8 shows the energy density distribution and Ohmic loss in the graphite susceptor.

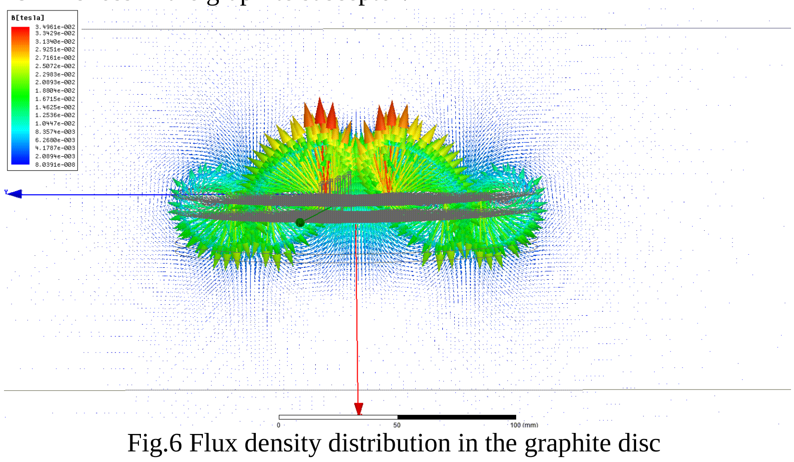

Fig.6 Flux density distribution in the graphite disc

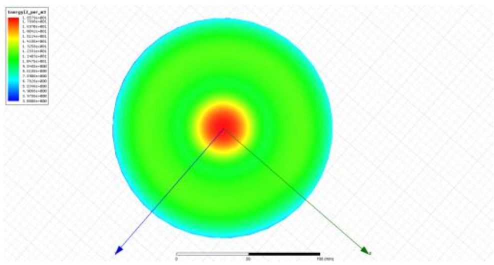

Fig.7 Energy density distribution plot of the graphite disc

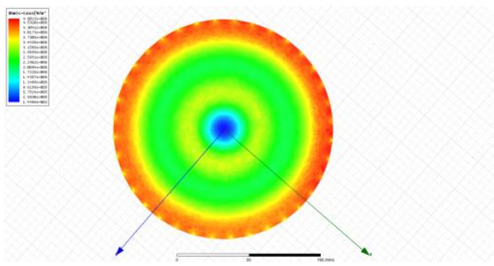

Fig.8 Ohmic loss plot of the graphite disc

V. CONCLUSION

The difference in phase angles between the coil currents results in a travelling wave magnetic field that offers better heat distribution in the susceptor because the flux lines are perpendicular to the work piece. The energy density plot of the graphite disc shows that by adjusting the coil current amplitudes without changing frequency nearly uniform heating can be achieved.

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