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Two-dimensional Sample Temperature Modeling in Separation by Plasma Implantation of Oxygen (SPIMOX) Process

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Two-dimensional Sample Temperature Modeling in Separation by Plasma Implantation of Oxygen (SPIMOX) Process

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Abstract

Plasma immersion ion implantation (PIII) offers high throughput and efficiency in the synthesis of silicon-on-insulator (SOI) materials. In the separation by plasma implantation of oxygen (SPIMOX) process, the spatial and time variation of the sample temperature must be known and well controlled to ensure uniform buried oxide and silicon overlying layer thicknesses over the entire silicon wafer. In this paper, we describe a two-dimensional model and derive the temperature distribution on the silicon wafer with respect to time and other process parameters. Our results show laterally non-uniform heating by the incoming ions and the local temperature is influenced more by the sample voltage and thermal irradiation coefficient of the target than the pulse duration and plasma density. The model provides a simple and quick means to determine whether external heating will be needed to maintain the sample temperature at 600°C during the SPIMOX process.

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I. INTRODUCTION

Silicon-on-insulator (SOI) is the preferred substrate for low-power, high-speed microelectronic devices, but suffers from high materials cost compared to bulk silicon [1]. In both the separation by implantation of oxygen (SIMOX) and Smart-Cut® processes, the high manufacturing cost stems from the long time needed to implant a sufficiently high dose of oxygen or hydrogen, and the throughput is lower for larger wafers. Because the implantation time is independent of the wafer size, plasma immersion ion implantation (PIII) is a more efficient approach than beam-line ion implantation with regard to SOI formation [2-9]. The high ion dose rate and small equipment footprint are additional advantages.

In either the SIMOX or separation by plasma implantation of oxygen (SPIMOX) process, the sample temperature during implantation must be kept at 600°C [1]. In the SPIMOX process, since the ion dose uniformity depends on the process conditions and sample chuck geometry, the heat input due to incoming ions may not be uniform over the entire wafer and if the variation is large, local defects as well as non-uniform buried oxide and silicon overlayer thicknesses may result. This temperature variation can in fact impact the outcome of non-semiconductor PIII applications [10].

Even though direct temperature monitoring is highly desirable in PIII, the high sample voltage and electrical / magnetic interference render common temperature measurement techniques impractical. It is even more difficult to measure in real time the temperature on multiple areas of the wafer. It is thus important to develop a model to map the temperature gradient over the entire sample. Blanchard developed a simple, time-dependent, lumped capacity thermal model [11], but unfortunately, it cannot provide multi-dimensional

temperature information. In order to simulate the target temperature more accurately, a two-dimensional model combining a plasma fluid model with the non-steady-state heat transfer formalism has been proposed [12]. In this work, we apply the model to investigate the SPIMOX process.

II. SIMULATION

The hardware parameters are based on the semiconductor PIII machine operating at the City University of Hong Kong and the instrument has been described in details elsewhere [13]. In our simulation, a 100 mm silicon wafer is laid on top of a 152 mm diameter, 52 mm thick stainless steel sample platen, and the high voltage feedthrough is shielded by a quartz tube. Our model takes into account ions implanted into all areas including the silicon wafer and exposed sample platen (brim, side, and bottom).

The incident ion flux is derived by simulating the temporal sheath expansion using a two-dimensional fluid model [14-16]. The target is immersed in oxygen plasma with density n_0 that is assumed to be spatially uniform before each voltage pulse. The evolution of the ion density n_i, ion velocity v_i, and potential ϕ is modeled using cold, collissionless fluid ions, Boltzmann electrons and Poisson's equation. In cylindrical coordinates, the two-dimensional equations of ion continuity and motion, Poisson's equation and Boltzmann relationship are:

$$\frac{\partial n}{\partial \tau}+\frac{1}{R}\frac{\partial}{\partial R}(Rnu_R)+\frac{\partial}{\partial Z}\left(nu_z\right)=0 \qquad (1)$$

$$\frac{\partial u_R}{\partial \tau}+u_R\frac{\partial u_R}{\partial R}+u_z\frac{\partial u_R}{\partial Z}=\frac{1}{2}\frac{\partial \varphi}{\partial R} \qquad (2a)$$

$$\frac{\partial u_z}{\partial \tau}+u_R\frac{\partial u_z}{\partial R}+u_z\frac{\partial u_z}{\partial Z}=\frac{1}{2}\frac{\partial \varphi}{\partial Z} \qquad (2b)$$

$$\frac{\partial^2\varphi}{\partial R^2}+\frac{1}{R}\frac{\partial\varphi}{\partial R}+u_z\frac{\partial^2\varphi}{\partial Z^2}=2\left[n-\exp\left(\frac{e\phi_t}{kT_e}\varphi\right)\right] \qquad (3)$$

The normalized dimensionless variables are $R = x/S_0$, $Z = z/S_0$, $\varphi = \phi/\phi_t$, $n = n_i/n_0$, $u_R = v_{iR}/v_{max}$, $u_Z = v_{iZ}/v_{max}$, $\tau = t/\omega_{pi}$, where $S_0 = (-2\varepsilon_0\phi_t/en_0)^{0.5}$ is the planar ion-matrix sheath width, $v_{max} = (-2e\phi_t/m)^{0.5}$ is the velocity that an ion would gain if it fell through a potential drop ϕ_t, and $\omega_{pi} = (n_0e^2/m\varepsilon_0)^{0.5}$ is the ion plasma frequency. The equations are solved by the finite difference method. The simulation parameters are chosen based on actual experimental parameters: $n_0 = 5.0\times10^{15}$ or $1\text{x}10^{16}$ m^{-3}, ϕ_t = -20 or –40 kV, kT_e = 4 eV, and an oxygen plasma (O_2^+). The spatial distribution of the deposited energy derived from the ion flux for each pulse at two accelerating voltages is shown in Fig. 1. Due to the symmetry of the sample stage, only a quarter of the sample platen (right half of the top and upper half of the side) is shown. It can be observed that heating from ions impacting the side of the sample platen is quite substantial.

Owing to the relatively small ion projected range compared to the substrate thickness, the process can be modeled as a semi-infinite, one-dimensional solid with a uniform surface heat flux. In order to obtain an upper bound for a single pulse, the conduction and radiation terms can be eliminated, and the equation becomes [11]: $T(0,t)=\frac{2q}{k}\sqrt{\frac{\kappa t}{\pi}}$, where κ is the thermal diffusivity, ρ = 8020 kg/m^3, c = 460 J/kgK, and k = 30 W/mK for stainless steel. For simplicity, we assume that heat conductance through the silicon wafer (from top to bottom) is instantaneous compared to that through the stainless steel platen. In this case, a single 18 µs pulse contributes a temperature rise of 0.76 K. This is in line with the results (about 0.7K) measued by *Chun*, et al [17] thereby confirming the validity of our model. As this value is relatively small, the target temperature can be modeled by averaging the input power over the

full cycle. The target temperature is simulated by solving the non-steady-state heat transfer equation by the finite difference method. In cylindrical coordinates, the equation is:

$$k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2}\right]+H=\rho c\frac{\partial T}{\partial T} \qquad (4)$$

where ρ is the density of the target materials, c is the heat capacity, k is the thermal conductivity, and H is the heating and cooling power corresponding to ion bombardment and thermal radiation. The energy deposited by the implanted ions is used as the input paramter. Heat loss by conduction via the high voltage feedthrough can be ignored on account of the thin stainless steel supporting rod. Therefore, the primary heat loss mechanism is radiation, and the thermal emissivity is assumed to be $\varepsilon = 0.5$. The vacuum chamber wall is water-cooled at 22°C, and we also assume that the target is initially at a temperature of 22°C or 295K.

III. RESULTS and DISCUSSION

The temperature distributions along the top (radial direction) and side (vertical direction) of the sample platen after 1, 300, and 1800 seconds implantation time are depicted in Fig. 2. The oxygen implantation conditions are: voltage = -40kV, pulse width = 18µs, plasma density = $5\text{x}10^{15}$ m^{-3}, and pulsing frequency = 300 Hz. It can be observed that the temperature near the side of the target (large radial and vertical distances) is higher than that near the center. It is interesting that there are three higher-temperature sites at the initial time stage (Fig. 2a) located at and near the sample edge. The temperature difference is not small across the entire target holder, but the radial variation along the top surface is only a few degrees within the silicon wafer range (100mm) although the heat input is more nonuniform. The target temperature rises rapidly initially but more slowly later due to higher radiation

heat loss at higher temperature. Based on the simulation results, the highest temperature induced by the incident energetic ions is 685K under these conditions, and so the implantation power must be increased in order to heat the sample to 873K (600°C) in the absence of external heating. Fig. 3 compares the influence of processing parameters on the equilibrium temperature at a pulsing frequency of 500 Hz without external heating or cooling. The results indicate that a variation of the implantation voltage has a larger effect on the target temperature than that of the plasma density or pulse duration. This trend is consistent with our experimental results obtained for different targets and processing parameters [18]. Fig. 4 shows the effect of the pulsing frequency on the equilibrium target temperature for a voltage of 40 kV, plasma density of $5x10^{15}$ m^{-3}, and pulse width of 18 μs. The rate of the temperature-rise gradually decreases with increasing pulsing frequency. The results indicate that it is not easy to reach 600°C using ion implantation alone. For instance, for $\varepsilon = 0.5$, a high frequency of 800 Hz is needed as shown in Fig. 4. If such a high power is not achievable due to hardware limitation, external heating must be used. The ability to calculate the ion heating power based on a chosen set of processing conditions is thus important to the process engineers in order to determine whether external heating is necessary. In addition, the temperature distribution over the entire silicon wafer derived from the model can be combined with an empirically determined temperature at one spot on the wafer using a pyrometer or thermocouple to enhance the accuracy. Fig. 5 also illustrates the effects of different radiation heat losses (ε = 0.5 and 0.1) and the needed heating power. The influence is quite significant and the heat emissivity of the sample chuck surface should also be considered when designing the PIII conditions. A silicon-compatible coating with low heat emissivity may reduce heat loss enough to allow for the use of a lower frequency or power or simply require some form of non-contact radiation heating.

IV. CONCLUSION

A simple model is used to predict and explain the sample temperature distribution during oxygen PIII in the SPIMOX process. The method employs a two-dimensional fluid model and temperature governing equation to describe the temperature rise and variation on the sample. The results show that ion heating is spatially non-uniform even though the temperature gradient across the sample is not substantial. A variation of the implantation voltage has a larger influence on the target temperature than that of the plasma density or pulse duration. The model can be used to determine whether external heating is necessary for different processing conditions. The results also indicate that heat loss due to radiation is very significant in the SPIMOX process and a suitable coating materials on the sample chuck may obviate the need for an external heating source. Last but not least, the model can be combined with the temperature measured experimentally oin one spot of the wafer to more accurately determine the lateral temperature distribution. The model can be easily applied to other PIII processes, e.g. water or hydrogen PIII by simply replacing oxygen with the appropriate ion species.

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Figure Captions:

Fig. 1: Calculated ion (heating) flux distributions along the top and side of the sample platen at 20 kV and 40 kV accelerating voltages. Only a quarter of the sample stage (right half of the top and upper half of the side) is shown due to symmetry. Distance from 0mm (center of platen) to 76 mm represents the top surface of the platen, whereas that from 76 mm to 102 mm indicates the side of the platen.

Fig. 2: Temperature variation on the top (radial direction) and side (vertical direction) of the sample platen after PIII after: (a) 1 s, (b) 300 s, and (c) 1800 s. Similar to Fig. 1, only a quarter of the sample platen is shown. The upper right corner of the sample platen has the coordinates: radial = 76 mm and vertical = 26 mm. The conditions are: sample voltage = -40 kV, pulse width = 18 μs, plasma density = 5×10^{15} m^{-3}, and pulsing frequency = 300 Hz.

Fig. 3: Equilibrium target temperature using a pulsing frequency of 500 Hz for different implantation voltage, pulse width, and plasma density: (1) voltage = -40 kV, plasma density = 1×10^{16} m^{-3}, pulse width = 12 μs, (2) voltage = -40 kV, plasma density = 5×10^{15} m^{-3}, pulse width = 18 μs, (3) voltage = -20 kV, plasma density = 5×10^{15} m^{-3}, pulse width = 12 μs, and (4) voltage = -40 kV, plasma density = 5×10^{15} m^{-3}, pulse width = 12 μs.

Fig. 4: Impact of the pulsing frequency on the equilibrium target temperature and external power needed to reach 600°C under conditions of voltage = -40 kV, plasma density = 5×10^{15} m^{-3}, pulse width = 18μs. The solid symbols represent $\varepsilon = 0.1$ whereas the open symbols represent $\varepsilon = 0.5$.

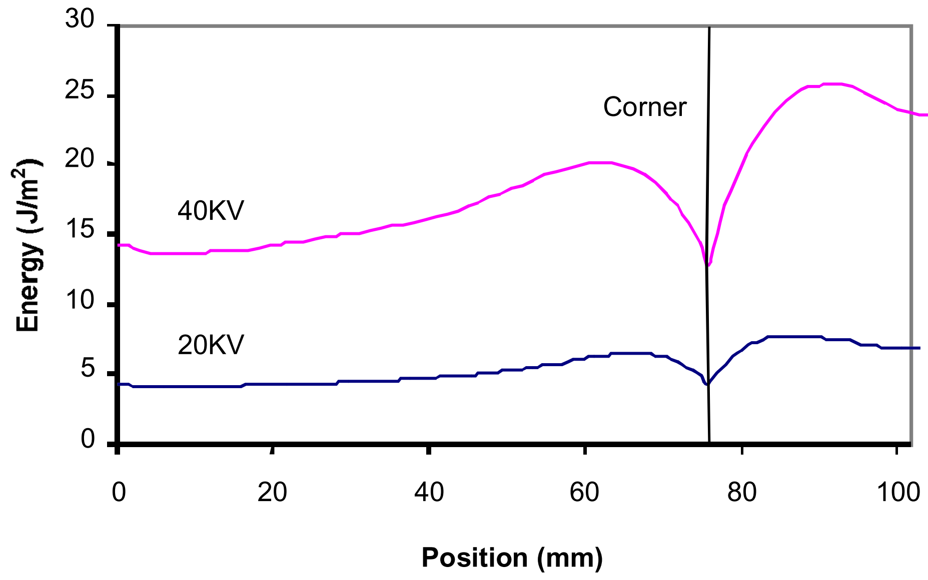

Fig. 1

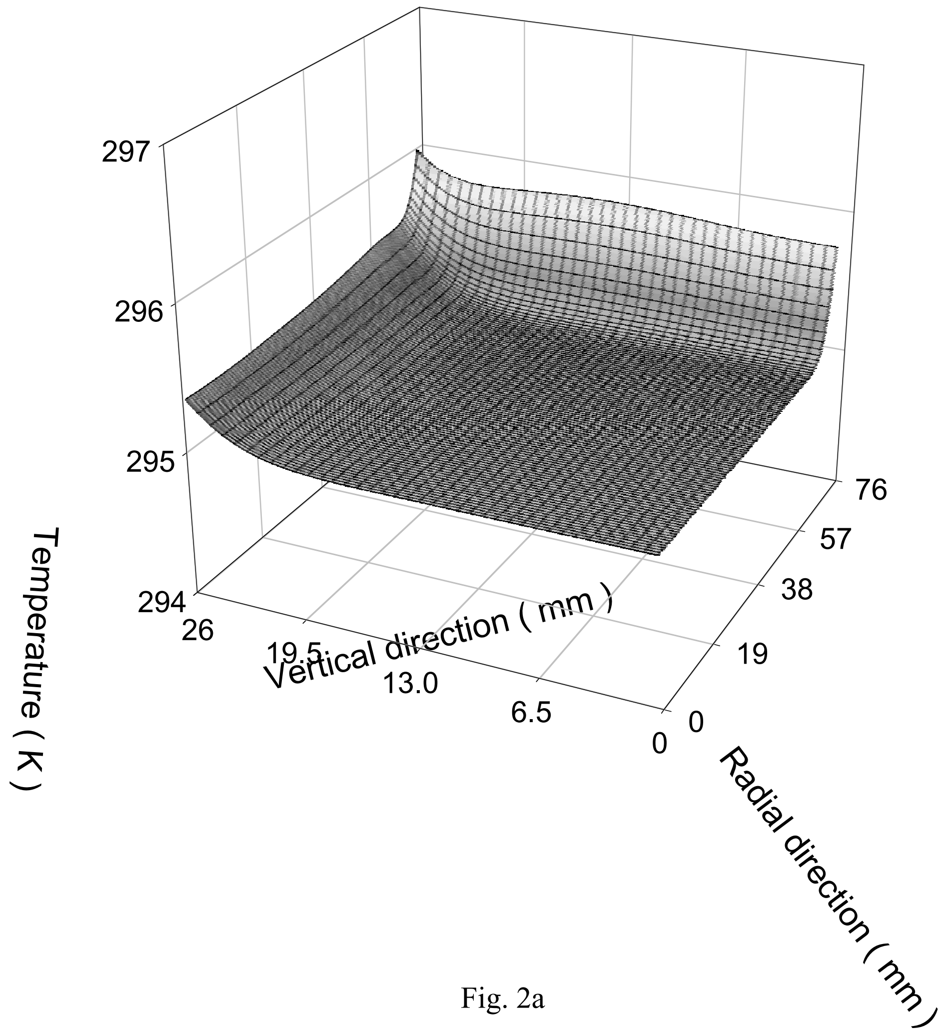

Fig. 2a

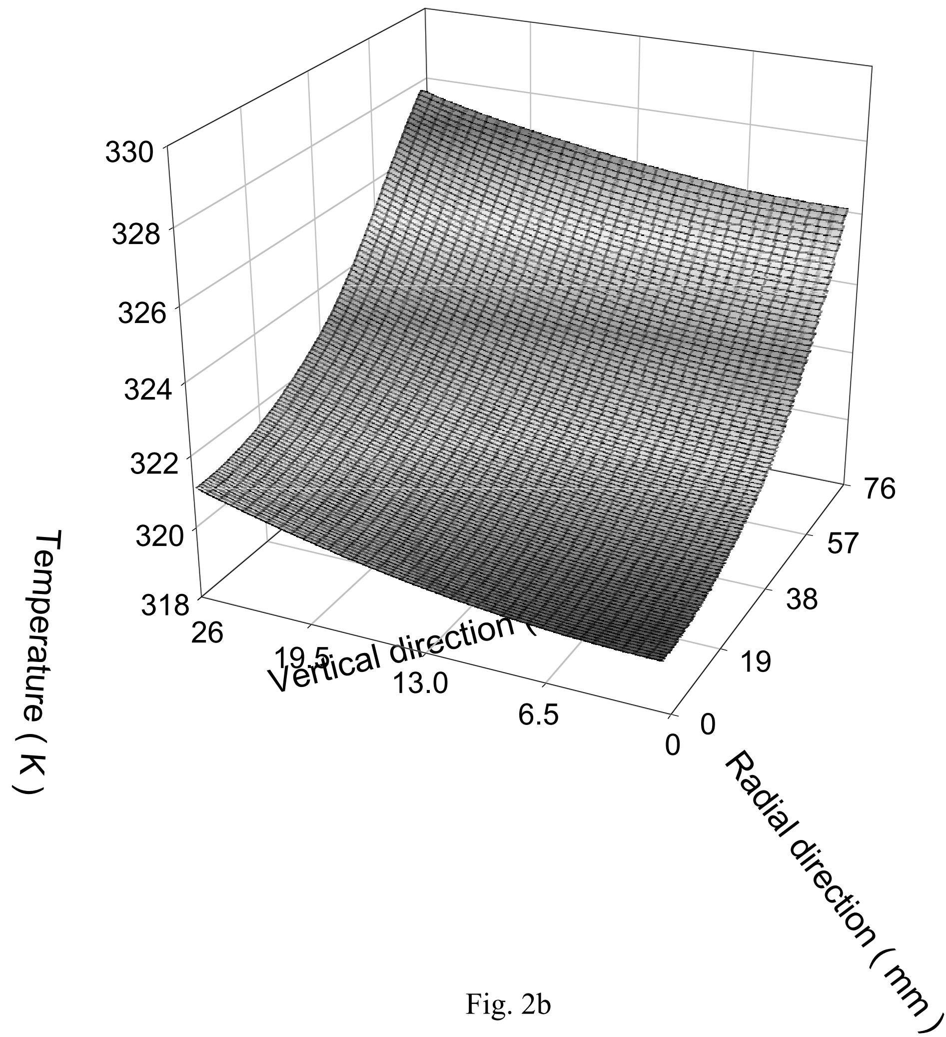

Fig. 2b

1800S

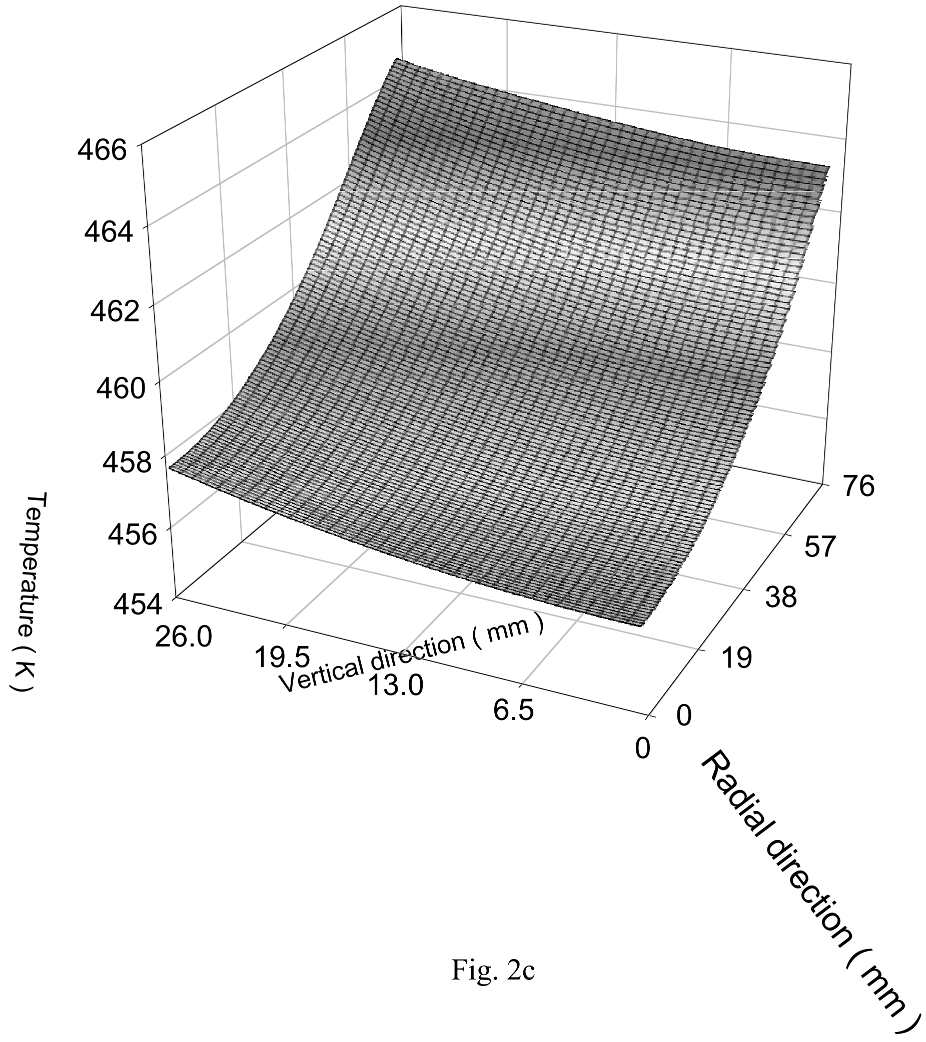

Fig. 2c

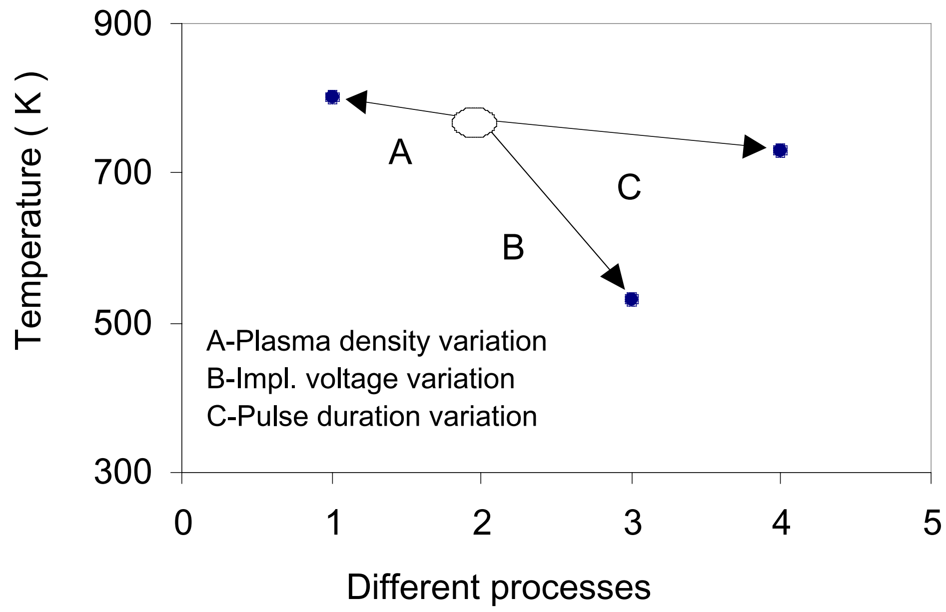

Fig. 3

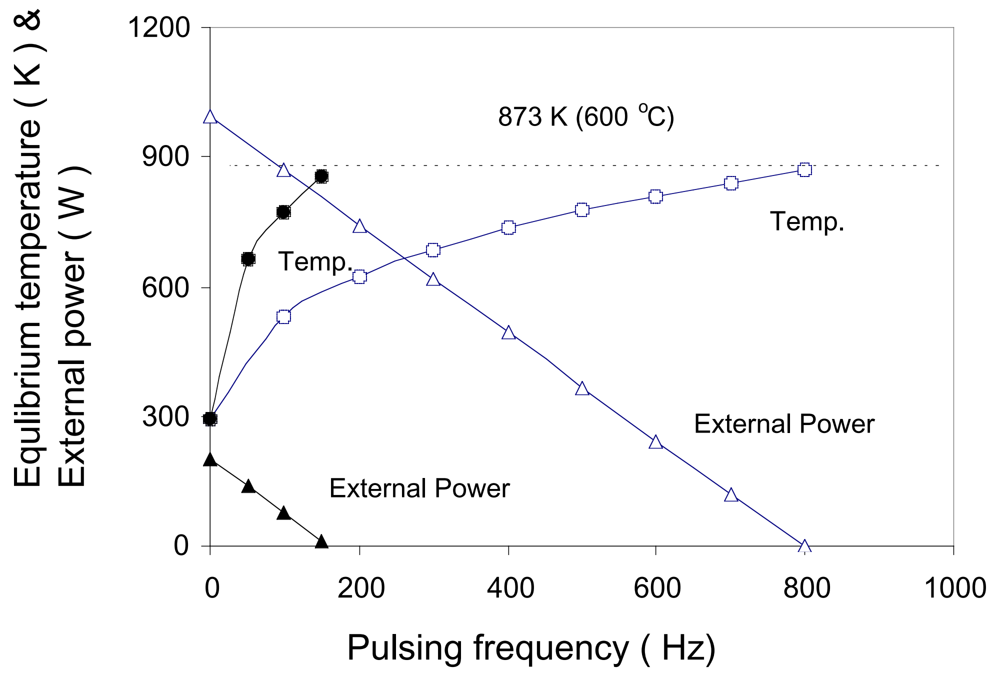

Fig. 4

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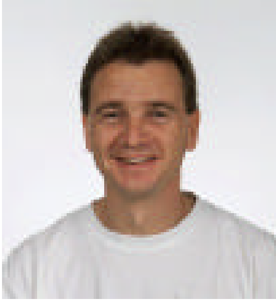

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