Electromagnetic Annealing for the 100 nm Technology Node

K. Thompson, J. H. Booske, Y. B. Gianchandani, and R. F. Cooper

***Abstract*—Electromagnetic induction heating (EMIH) is a novel rapid thermal processing technique that uses microwave and radio frequency (RF) radiation to directly heat silicon wafers. Heating rates of 125 °C/s have been achieved and 75 mm diameter wafers have been heated above 1000 °C using only 950 W of power. EMIH has been used to activate shallow implanted dopants with minimal diffusion of the junction depth. It is speculated that the exposure of the wafer to intense electric fields during the anneal may provide an additional driving force for dopant activation, allowing for higher activation at lower temperatures. Post-anneal junction depths less than 25 nm with sheet resistances between 700 and 1000 ohms/square have been achieved without the use of a controlled low oxygen ambient. The EMIH Rs-Xj curve penetrates the SEMATECH 100 nm technology box and with further optimizations may satisfy the 70 nm technology node.**

***Index Terms*—Anneal, dopant, radiation, rapid.**

I. INTRODUCTION

THE NEED to reduce the thermal budgets of next generation device processing has created significant interest in short-term rapid thermal processing (RTP) of silicon. The most pressing application of RTP is the formation of the S/D regions of the CMOS gate stack. Device operation is optimal when these doped regions are kept as box-shaped as possible [1], [2]. Deviation from this box-shaped profile reduces the $I_{\text{drive}}/I_{\text{off}}$ ratio increases threshold voltage rolloff, detrimentally reduces the minimum gate length, and increases the gate-drain capacitance.

To achieve such profile control, annealing times and temperatures must be precisely controlled to minimize the diffusion of the implanted species. Unfortunately, this reduction of the thermal budget inhibits activation of the implanted dopants, rendering them ineffective and driving up the parasitic contact resistance. While the current SEMATECH technology benchmark [3] meets the 0.13 μm technology node, this tradeoff causes it to fall short of the 0.1 μm requirements. Techniques that activate significantly higher percentages of implanted dopants while minimizing diffusion are necessary for next generation technology.

One such recent success in dopant activation is electromagnetic induction heating. EMIH utilizes either RF (1–300 MHz) or microwave (300 MHz–10 GHz) radiation to rapidly heat silicon to temperatures at which activation occurs. Besides the rapid ramp rates and precise control over final temperature (through control of the input power), it is speculated that the presence of intense electric fields during the annealing process may provide an additional driving force for dopant activation. Such a force has been shown to exist elsewhere, for example in the transport of ions during microwave processing of ceramics [4].

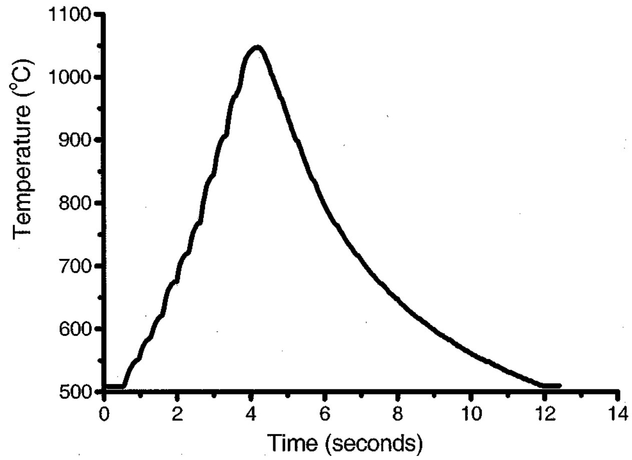

Fig. 1. Temperature transient for a 75 mm silicon wafer heated in the microwave system in the TM111 mode at 1000 W.

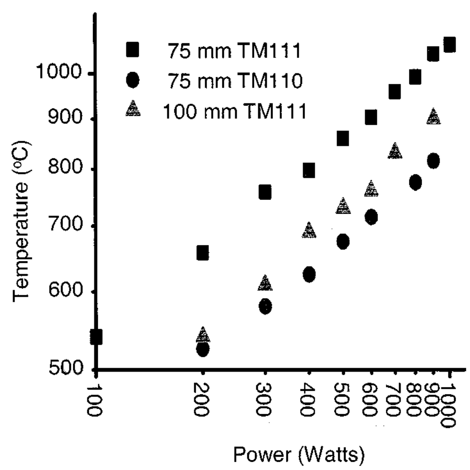

Fig. 2. Steady-state temperature (in degrees Celcius) of wafers heated in the microwave cavity for various powers and wafer diameters. There is a notable loading effect with diameter because power loss is related to the surface area of the wafer.

II. EXPERIMENTAL APPARATUS

In the microwave regime, EMIH was performed in a resonant cavity (diameter 17 cm) with a height that could be adjusted to tune in specific modes. A radial tuning stub helped minimize reflected power and up to 3000 W was available from a fixed

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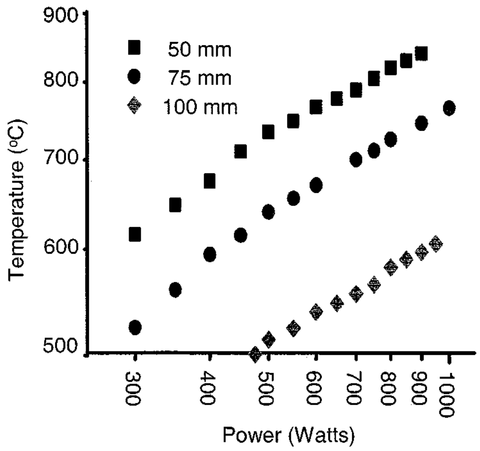

Fig. 3. Steady state temperature (°C) of wafers heated in the RF system for various powers and wafer diameters. Again there is a notable loading effect with diameter because power loss is related to the surface area of the wafer.

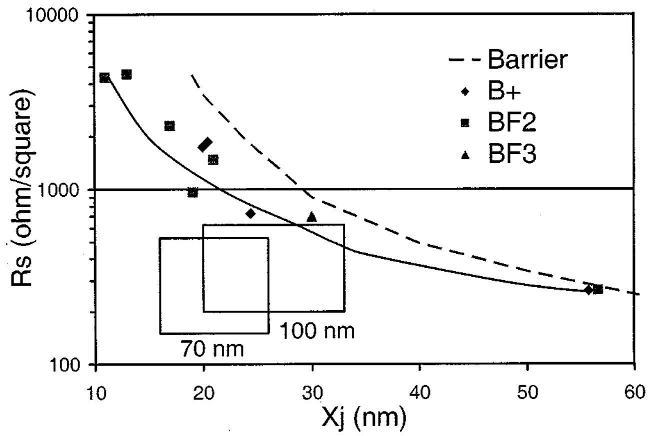

Fig. 4. Rs versus Xj plot of results. The EMIH anneals, performed in an uncontrolled ambient, correlate well with the best data to date, performed in 33-ppm oxygen in a nitrogen purge, taken by Lerch *et al.* [9] at Mattson. EMIH annealing may extend this new curve into the 70 nm technology node.

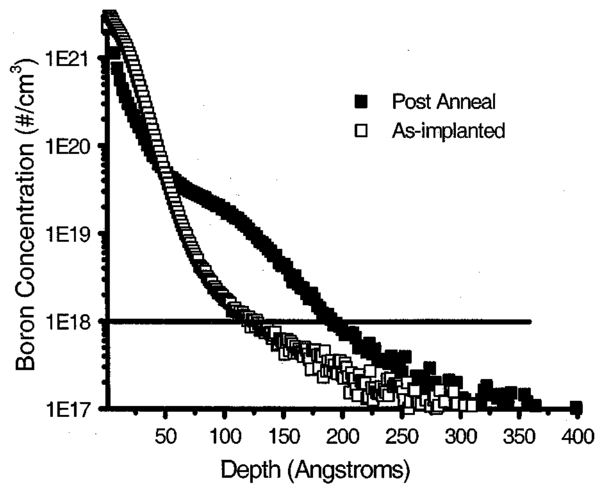

Fig. 5. Profile of boron concentration before and after anneal for BF_2 implant at 1100 eV and $5 * 10^{15}/cm^3$ dose. Very little diffusion ~ 6.5 nm occurs for a resulting sheet resistance of 950 Ω/sq.

frequency (2450 MHz) magnetron source. Although several resonant modes were found, the dominant TM111 and TM011 modes were used. The wafer, supported by a quartz cylinder 1 mm above the cavity bottom, was in a magnetic field maximum. In the radio frequency (RF) regime, magnetic flux was excited with a spiral copper antenna. One thousand Watts was available from a fixed frequency, 13.56 MHz power supply. The wafer was positioned on a ceramic chuck 2.5 cm below the coil, in the extreme near field of the antenna.

Electromagnetic heating is strongly dependent on the magnetic field pattern. As such, heating uniformity depends on the specifics of the apparatus employed. This presents an obstacle to scaled up implementation and is a subject of ongoing research. A previous publication discusses the issue of heating uniformity and gives greater details about the experimental systems [5]. In this publication, all results are taken at the wafer center unless otherwise specified.

An optical pyrometer allowed the temperature to be accurately measured without perturbing the field patterns. Recognizing that silicon is not an ideal black body radiator, the pyrometer was calibrated to the specific emissivity of silicon via solid-state reactions in the temperature range of interest (800–1100 °C) [5].

III. Experimental Results

Several silicon wafers, both n- and p-type, ranging from near intrinsic ($\rho = 500\ \Omega$-cm) to highly doped ($\rho = .001\ \Omega$-cm), with radii of 25, 50, 75, and 100 mm have been rapidly heated to temperatures in excess of 1000 °C. Fig. 1 shows the heating transient of an n-type, near intrinsic, 75 mm wafer heated in the microwave cavity (TM111 mode). The temperature ramp rates for wafers whose room temperature impurity levels varied from near intrinsic to highly doped are almost identical to that shown in Fig. 1. This is not unexpected since above 500 °C the number of free carriers (electrons and holes) in silicon is dominated by the intrinsic carrier concentration. It is this free carrier concentration that determines wafer conductivity, a key parameter in the coupling of electromagnetic waves to silicon [5]. At room temperature the free carrier concentration is determined by wafer doping; consequently, heating rates below 500 °C depend heavily on dopant levels.

Log plots of temperature versus power for the microwave and RF systems, Figs. 2 and 3, exhibit the relationship between power absorbed and power loss that determines the steady-state temperature. A fourth root dependence of power to temperature is realized from the data, indicating that above 500 °C radiation dominates the thermal loss mechanism. The heating efficiencies of the TM111 and TM011 modes, dependent on the individual magnetic field patterns transverse to the wafer surface, are distinguished and the loading effect of different diameter wafers can clearly be seen.

To test the effectiveness of this technique for ultra shallow junction formation, several wafers were implanted with BF_2 or B^+ under varying conditions of dose or energy and spike annealed to temperatures between 900 °C and 1050 °C in either the microwave or RF system. Annealing was performed in an uncontrolled ambient at atmospheric pressure. Sheet resistance (Ω/sq) and junction depth (nm at $10^{18}/cm^3$) data, provided by a four-point probe and SIMS analysis, are plotted in Fig. 4. As a comparison, the standard SEMATECH technology benchmark

[3] is shown as a dashed line. Data points to the southwest of this curve indicate an improvement over the benchmark due to either a higher percentage of activated dopants or a more box-like (less diffusion) profile. Progress in doping or annealing techniques can be tracked by the boxes, which indicate technology node requirements.

SIMS results showing the as doped and post anneal profiles for a $5 \times 10^{15}/\mathrm{cm}^2$ dose of BF_2 implanted at an energy of 1100 eV are shown in Fig. 5. A sheet resistance of 950 ohms/square has been achieved with remarkably little diffusion, 6.5 nm. This data point, along with several others fall below the SEMATECH curve in Fig. 4 and create a new line representing either improved activation or a more efficient, box-like, dopant profile. This may indicate the presence of an additional driving force during annealing, possibly due to some yet unidentified interaction between the high frequency electric field and the silicon lattice. It is well established that reaction kinetics in certain materials are enhanced when high frequency electric fields are present. [4] Future experiments are planned to examine this possibility.

Improvements on these results should come with a better controlled and more rapid temperature ramp and cool rate along with an optimized annealing time and temperature. In addition, it has been shown that a controlled ambient of 33 ppm oxygen in a nitrogen purge is the optimal environment for ultrashallow dopant annealing [1]. This tightly controlled, low-oxygen ambient allows just enough of a surface oxide to be grown to limit the out-diffusion of boron from the wafer while consuming a minimal amount of silicon during the oxidation process. Furthermore, this ambient eliminates oxygen-enhanced diffusion. Annealing in this controlled ambient appears to yield approximately 15% less junction diffusion for a given level of activation when compared with annealing in an uncontrolled ambient. While the current results satisfy the 100 nm technology node, the optimizations just described may push the EMIH "technology curve" into the 70 nm box, resulting in a significant improvement over standard RTP technology.

IV. Conclusion

Electromagnetic heating of silicon has been performed at relatively low frequencies, 13.56 and 2450 MHz, in both a resonant and nonresonant cavity. Radiation at these frequencies can be generated at low cost with standard equipment. Furthermore, the possibility of an additional driving force may achieve anneal results superior to those possible through conventional techniques.

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