Surface Heat Treatment of Silicon Wafer Using a Xenon Arc Lamp and Its Implant Activation Applications

Woo Sik Yoo* and Kitaek Kang

WaferMasters, Inc., San Jose, California 95112, USA

A surface heat-treatment method for semiconductor wafers using a xenon arc lamp is described. High absorption coefficients of silicon wafers in ultra violet (UV) region and short process time made selective surface heating possible. The surface melting of entire 150 mm diameter Si wafers was demonstrated in less than 2 s at a lamp power of 15 kW. By focusing UV light into a limited area on Si wafer surface, surface melting of a selectively exposed area was demonstrated at a much lower power. The surface temperature ramp rate is estimated to be on the order of 1000°C/s. Si wafers, with various implanted species (P⁺, As⁺, B⁺ and BF₂⁻) and energies (1 keV–70 keV), were annealed for implant damage recovery and electrical activation using the Xe lamp under different scanning speeds. Sheet resistance and secondary ion mass spectroscopy (SIMS) depth profiling measurement results from the scanning rapid thermal annealing (RTA) successfully demonstrated the feasibility of the technique in semiconductor RTA processing applications. Electrical activation with desired levels of dopant diffusion can be achieved by optimizing process variables such as lamp power, distance between the lamp and Si wafer, area of light exposure and scanning speed.

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Rapid thermal annealing (RTA) is one of the hottest areas of interest in advanced Si device fabrication. Typical RTA systems employ either halogen lamps or a resistively heated furnace or susceptor as heat source. The lamp-based RTA systems have an excellent lot size flexibility as well as flexibility in controlling a process temperature profile while they have very poor energy efficiency and require complicated temperature measurement/control algorithms. Although the resistive heating-based RTA systems do not provide the same lot size flexibility, they provide equivalent process results at much higher energy efficiency.

A very fast wafer heating and cooling, called “spike anneal” is proposed to electrically activate implant species while suppressing unwanted dopant diffusion during (ultra)shallow junction implant anneal. However, conventional tungsten halogen lamp-based RTA techniques heat the Si wafer and wafer temperature ramp up and ramp down rate are limited to ~200°C/s and ~90°C/s, due to the balance amongst the heating/cooling characteristics of tungsten filaments, heat capacity of Si wafer and heat loss from the wafer, and so on. Increase in lamp power and/or number of lamps simply do not improve wafer temperature ramp up and ramp down characteristics. Large size wafers make the fast wafer heating and cooling more difficult in conventional tungsten halogen lamp-based RTA techniques. The spike anneal using Ar arc lamp has been demonstrated. The reported wafer temperature ramp rate and cooling rate were 400°C/s and 180°C/s, respectively.

In advanced Si devices, all the active device areas are located at the top surface (up to 1 μm from the surface) of 600 ~ 800 μm thick Si wafers. Selective surface heat-treatment is ideal from the viewpoint of fast heating/cooling at minimum energy consumption, dopant diffusion reduction, and prevention of defect generation during thermal cycle. Several different short time (femtosecond (fs) to millisecond (ms)) annealing approaches, using various wavelength light sources (from ultraviolet (UV) to far infrared (FIR)), have been investigated. Feasibility of laser thermal annealing (LTA) in ultra shallow junction implant anneal using short wavelengths (308 nm XeCl and 248 nm KrF) pulsed excimer lasers has been demonstrated. All solid state lasers in the visible and near infrared (NIR) region in the nanosecond (ns) and millisecond (ms) time scale have been investigated for industrial applications. Carbon dioxide (CO₂) LTA (λ = 10.6 μm) utilizing energy transfer from excited carriers to the lattice via electron-phonon scattering has also been investigated and demonstrated for local heating of Si lattice. Flash annealing (FLA) using Xe lamp(s) also showed successful short time surface heating of Si for (ultra)shallow junction implant annealing. Due to the complex behavior of implant species, in particular high concentration of implanted B and BF₂ in Si, combinations of LTA + RTA, RTA + LTA, FLA + RTA and RTA + FLA are being actively investigated for desired implant activation results with minimized adverse effects of advanced annealing such as dopant diffusion and deactivation.

In this paper, a xenon (Xe) arc lamp-based surface heat-treatment system and method for semiconductor wafers is proposed. A surface melting experiment was performed to demonstrate the feasibility of surface heat-treatment of Si wafers using a Xe arc lamp. Si wafers with various implant species and energies were translated at a different rate under focused UV to NIR light for implant activation annealing. The wafers were annealed with a scanning mode of RTA. The annealed Si wafers were characterized for electrical activation and dopant diffusion as a function of scanning (wafer translation) speed. The difference in wafer heating mechanisms between the tungsten halogen lamp-based system and Xe arc lamp-based system is discussed.

Experimental

Experimental set up.— A Xe arc lamp with 200 mm gap between electrodes was used with two different types of reflectors. Figures 1a and 1b show configurations of the lamp, reflector and wafer for entire

Figure 1. Configurations of lamp and reflector assemblies for (a) entire surface heat-treatment and (b) selective surface heat-treatment.
The surface heat-treatment and selective surface heat-treatment, respectively. 150 mm diameter Si wafers were used as heating objects in this experiment.

As a first step of the experiment, the entire front surface of the wafer was heated using the Xe arc lamp configuration shown in Fig. 1a under different experimental conditions. Lamp power, exposure time and distance between the envelope of the flow tube for the Xe arc lamp (lamp assembly) and the center of the wafer were mainly varied. When the lamp power and distance were kept at 20 kW and ∼50 mm, pitting and partial wafer surface melting were observed areas where strong light was irradiated. The pitting, crystalline slip generation and partial wafer surface melting were observed with as short as 1 s of exposure. As time increases, pitted and molten surface area increased. The entire surface was melted within 7 s of exposure. Wafers with exposure time longer than 7 s showed severe wafer warpage and thickness variation across the wafer due to the molten zone movement and change in surface tension of Si wafer during heat-treatment. Many Si droplets were also observed on the back side of wafers. A very fast temperature increase resulted in sudden Si vapor pressure increase and pressure build up on the back side of the wafer, as well. By reducing the distance between light source (lamp assembly) and wafer, the surface melting took place much faster at a lower lamp power. Figure 2 shows a surface molten and recrystallized Si wafer under unfocused irradiation from a Xe arc lamp. The lamp power and exposure time were 15 kW and ∼25 mm. An abrupt wafer surface melting was observed only below the slit. The surface melting in the irradiated area was observed in wafers exposed for annealing as short as 1 s. Figures 3a and 3b show the front and back side of wafer after selective surface heat treatments in three different areas. The experimental setup and procedure are illustrated in Fig. 3c. Three abrupt stripe patterns of molten and recrystallized zones were observed on the front surface while no visual damage was observed on the back side of wafer. The experimental result suggests feasibility of instantaneous surface heat-treatment of Si wafers using a Xe arc lamp at a relatively low energy level. Very fast and uniform surface heat-treatment of Si wafers is feasible at a reasonable power consumption level without

Implanted silicon wafers.—To test the feasibility of surface heat-treatment of Si wafers using a Xe arc lamp in the scanning mode, six different types of implanted 150 mm Si(100) wafers were prepared. Various implanted species (P⁺, As⁺, B⁺ and BF₂⁺) and energies (1 keV - 70 keV) were used for ion implantation. The P⁺ and As⁺ were implanted into p⁻Si(100) wafers to form np junctions after implant activation RTA. The B⁺ and BF₂⁺ ions were implanted into n⁻Si (100) wafers for pn junctions after implant activation RTA. The ion dose was fixed at 1.0×10¹⁵ cm⁻² for all implanted Si wafers. The list of implanted Si wafers and their implant conditions are summarized in Table I.

Table I. List of implanted wafers and their implant conditions.

| Series | Species | Energy | Dose      | Si Wafer Conduction Type |
|--------|---------|--------|-----------|-------------------------|
| A      | P⁺      | 20 keV | 1.0×10¹⁵ cm⁻² | p-type                  |
| B      | P⁺      | 70 keV | 1.0×10¹⁵ cm⁻² | p-type                  |
| C      | As⁺     | 20 keV | 1.0×10¹⁵ cm⁻² | p-type                  |
| D      | As⁺     | 70 keV | 1.0×10¹⁵ cm⁻² | p-type                  |
| E      | B⁺      | 1 keV  | 1.0×10¹⁵ cm⁻² | n-type                  |
| F      | BF₂⁺    | 3 keV  | 1.0×10¹⁵ cm⁻² | n-type                  |

The sheet resistance (Rs) of implanted wafers was measured from the implant side using four point probes after implant activation RTA in the scanning mode. Assuming reasonable junction integrity, including sufficient implant damage recovery and lower junction leakage, the implanted layers and Si(100) wafers were electrically isolated by the np or pn junctions Depth profiles of implant species (P, As and B) were measured by secondary ion mass spectroscopy (SIMS) before and after implant activation RTA for insight into dopant distribution and thermal characteristics of the surface heat-treatment in the scanning mode.

Results and Discussion

Surface heating.—The selective surface heat-treatment was attempted using the Xe arc lamp configuration shown in Fig. 1b. The reflector with a linear slit (∼2 mm in width and 200 mm in length) was installed in the cooling water flow tube to limit the area of exposure. The wafer was placed under the lamp assembly. The lamp power and distance between lamp assembly and wafer were kept at 15 kW and ∼25 mm. An abrupt wafer surface melting was observed only below the slit. The surface melting in the irradiated area was observed in wafers exposed for annealing as short as 1 s. Figures 3a and 3b show the front and back side of wafer after selective surface heat treatments in three different areas. The experimental setup and procedure are illustrated in Fig. 3c. Three abrupt stripe patterns of molten and recrystallized zones were observed on the front surface while no visual damage was observed on the back side of wafer. The experimental result suggests feasibility of instantaneous surface heat-treatment of Si wafers using a Xe arc lamp at a relatively low energy level. Very fast and uniform surface heat-treatment of Si wafers is feasible at a reasonable power consumption level without

Figure 2. Surface molten and recrystallized 150 mm-diameter Si wafer under entire surface irradiation from a Xe arc lamp. (lamp power = 15 kW, distance between lamp assembly and wafer = 25 mm, irradiation time <2 s).

Figure 3. Selectively surface molten and recrystallized Si wafer: (a) front side, (b) back side and (c) schematic illustration of wafer cross-section. (lamp power = 15 kW, distance between lamp assembly and wafer = 25 mm, slit width ∼2 mm, irradiation time <1 s).
introducing thermally induced defects by scanning very intense light from a Xe arc lamp across the wafer at a reasonable scanning speed. The lamp power, distance between lamp assembly and wafer, slit width and scanning speed can be optimized for practical wafer annealing applications below the melting point of Si. The light power density per unit area can be controlled by adjusting experimental parameters mentioned above. Judging from the melting point (1420°C) of Si, the surface temperature ramp rate in this experiment is estimated to be higher than 1400°C/s.

**Implant activation annealing.** Sheet resistance of various implanted Si samples were summarized in Fig. 4 as a function of scanning speed of a Xe arc lamp annealing at a fixed lamp power of 15 kW. The scanning speed of 10–200 mm/s was tested. Since there was not enough electrical activation for all implanted Si wafers at a scanning speed faster than 150 mm/s, at the lamp power of 15 kW, Rs measurement data for the scanning speed range of 10–100 mm/s was plotted. Blue scale is for B and BF2 implanted samples and black scale for As and P implanted wafers.

P and As implanted Si already showed sufficient electrical activation at a scanning speed of ~80 mm/s. As the scanning speed is lowered, the Rs values decrease gradually due to the increase of implanted surface temperature. For P and As implanted Si wafers with implant energy of 20 keV, significant Rs reduction at a scanning speed of 10–100 mm/s was observed. Blue scale is for B and BF2 implanted Si wafers and black scale is for As and P implanted Si wafers.

B and BF2 implanted Si wafers showed very high Rs values even at a slow scanning speed, while P and As implanted Si wafers showed lower Rs values. B implanted Si wafers were more difficult to activate the implanted species than the BF2 implanted Si wafers, at the same scanning speed. We suspect the surface temperature of B implanted and BF2 implanted Si wafers were significantly different at a given scanning speed. This is likely to be due to the difference in the photon coupling efficiency between B implanted and BF2 implanted Si wafers in the UV region. In our previous study of ultrashallow junction (USJ) implant annealing, significant variations of reflectance spectra from UV to NIR regions was observed from Si wafers with different implant species, energies and doses. In fact, the surface of the As (20 keV, 1.0×1015 cm−2) and BF2 (3 keV, 1.0×1015 cm−2) implanted Si wafers (Wafer C and F) was partially amorphized. This partial amorphization of the surface leads to a modification of the optical properties of the material and the coupling between the Xe radiation and the implanted Si wafers (Wafer C and F). A possible difference in radiation absorption between B implanted and BF2 implanted Si could be largely affected by the difference in the coupling efficiency of the Xe radiation and the implanted Si wafers (Wafer E and F).

SIMS depth profiles of implant species of various implanted Si samples, before and after the surface heat-treatment in scanning mode, were plotted in Fig. 5 as a function of scanning speed of the Xe arc lamp annealing at a fixed lamp power of 15 kW. For P+ and As+ implanted Si wafers, no dopant diffusion was measured at a scanning speed of 70 mm/s, regardless of implant energy, while sufficient electrical activation was confirmed from the Rs measurements. Significant dopant diffusion was observed from both 20 keV and 70 keV P+ implanted Si after the surface heat-treatment at scanning speeds of 50 and 33 mm/s (Figs. 5a and 5b). Very little dopant diffusion was measured from 70 keV As+ implanted Si wafers with scanning speeds of 50 and 33 mm/s, while noticeable dopant diffusion was measured from 20 keV As+ implanted Si wafers with scanning speeds of 50 and 33 mm/s (Figs. 5c and 5d). The same dose with lower implant energy results in shallower implant depth and higher maximum dopant concentration. Since one of important factors for dopant diffusion is the difference in concentration between the diffusing layer (implanted layer) and host material (Si wafer), the implanted wafers with lower implanted energy results in large differences in concentration. Thus, dopant diffusion is larger in implanted wafers with lower implanted energies for the same implant species and dose.

For B+ implanted Si neither shows sufficient electrical activation (Fig. 4), nor dopant diffusion (Fig. 5e), even in the slow scanning speed range of 17–25 mm/s, due to poor photon coupling in the UV range. On the other hand, BF2+ implanted Si wafers showed sufficient electrical activation and negligible diffusion at a scanning speed of 33 mm/s (Fig. 4 and Fig. 5e). Increased dopant activation and diffusion were observed at the slower scanning speeds of 25 and 20 mm/s.

**Discussion**

In lamp-based wafer heating techniques, the Si wafer absorbs emitted photon energy from lamps. Si has an absorption edge around wavelength of 1.2 μm and is transparent to the wavelength longer than 1.2 μm. The conventional tungsten halogen lamps operate at a filament temperature up to 3400 K and emit majority of photon energy in infrared (IR) region (~0.7 μm). The wavelength of maximum light intensity from a blackbody is expressed by Wien’s law (λmax = 2898/T [μm]). At tungsten filament temperatures of 2850 K and 3400 K, approximately 35% and 50% of integrated radiation power contribute for wafer heating. Only photons with higher energy (wavelength shorter than 1.2 μm) contribute to wafer heating by light absorption in Si. Since the absorption coefficient near the absorption edge is quite small, photons with lower energy near the absorption edge penetrate deeply into the Si wafer. They are absorbed not only by the surface but also the bulk during travel through the Si wafer. Some of them (unabsorbed photons) will be transmitted to the other side of the Si wafer. On the other hand, more than 90% of the integrated radiation power from a Xe arc lamp is located in the wavelength range of 0.2 ~ 1.2 μm. Approximately 80% of the integrated radiation power is emitted in the wavelength range of 0.2 ~ 0.9 μm. 10% of the integrated radiation power is emitted in UV region (0.2 ~ 0.4 μm).
Most of emitted photons from the Xe arc lamp contribute to wafer heating. Consequently, the wafer heating is very fast and efficient. UV light photons with wavelength shorter than 0.4 μm from the arc lamp are mostly absorbed by the surface of Si wafer due to the higher absorption coefficient ($\alpha = 2 \times 10^6 \sim 1 \times 10^7 \text{ cm}^{-1}$). This makes the Xe arc lamp suitable for very fast surface heat-treatment of Si wafers compared to the conventional RTA techniques using either tungsten halogen lamps or preheated heated susceptor.

The surface heat-treatment technique demonstrated using a Xe arc lamp is very promising for (ultra)shallow junction implant annealing applications, which are believed to require very fast heating and cooling of the active layer to electrically activate implant species while suppressing unwanted dopant diffusion. Deactivation of implanted B and As activated by high temperature annealing during subsequent annealing steps is well known. It is thought to be driven by the release of Si interstitials from end-of-range (EOR) defects. Suppression of deactivation nuclei is equally important as is the enhancement of electrical activation of dopants. While the LTA and FLA leave deactivation nuclei behind for subsequent thermal processing, due to the interaction between thermal quenching and EOR damage of implanted layer, the surface heat-treatment technique using a Xe arc lamp in subsecond time frames results in very fast surface heating with reasonable bulk heating (through fast heat dissipation to bulk Si) for suppression of the deactivation nuclei generation during cooling. This technique can also be applied to in situ impurity doping by diffusion near the melting temperature of Si in the presence of impurity species in atmosphere near the heated surface, as demonstrated in gas immersion laser doping (GILD).

As a surface heating method, pulsed XeCl laser-based technique has been proposed and demonstrated for shallow junction implant anneal. Talwar et al. reported that they were able to melt an amorphized implant layer and achieved abrupt shallow junctions in the range of 40 ~ 110 nm by radiating focused 308 nm laser beam (18 ns in pulse width and 0.55 ~ 0.90 J/cm² in power density). The high absorption coefficient of Si at short wavelength and short pulse width make surface melting possible. The absorption depth of Si at 308 nm is approximately 7 nm. Similar results were demonstrated using 248 nm (KrF) laser beam with a pulse duration of 38 ns. From the practical point of view, the laser-based annealing technique has difficulties in uniform heating of large areas. How to assure the process repeatability, uniformity and precise control focused laser beam to avoid overlaps between irradiated areas remains to be solved. In addition, scanning or repeating a focused beam over the entire wafer surface takes a relatively long time and it is rather impractical from the mass production point of view. For USJ B activation annealing, enhancement of photon coupling and/or preheating of implanted Si wafers would be required to avoid increasing the Xe lamp power and/or decreasing the scanning speed. For flash-lamp based implant activation annealing, “sub-second” heating pulse is applied to preheated implanted Si wafers to minimize flash lamp power and wafer breakage due to thermal shock. The Xe arc lamp line scan can also be effectively used for local growth of melted or deposited films such as...
We have demonstrated a surface heat-treatment method for semiconductor wafers using a xenon arc lamp. The high absorption coefficient of the silicon wafer in UV and visible regions and short process time made selective surface heating possible. A very fast and uniform surface heat-treatment of Si wafers is possible at a reasonable power consumption without introducing thermal defects by scanning high intensity UV and visible light from a Xe arc lamp across the wafer. The surface melting of entire 150 mm diameter Si wafers was demonstrated at a much lower lamp power. Lamp power, distance, between lamp assembly and wafer, light power density per unit area and scanning speed can be optimized for practical wafer annealing applications below the melting point of Si. The surface temperature ramp rate is estimated to be on the order of 1000 °C/s. The surface heat-treatment method with capability of selective area heating is suitable for RTA applications and it enables scanning RTA for advanced short time annealing applications which require reasonable rates of heat dissipation to the bulk Si to prevent unwanted thermal quenching during RTA. The RTA temperature ramp rate and heat dissipation rate (or temperature gradient from the surface to bulk Si) can be controlled by the combination of lamp power, slit width and scanning speed.

As a part of feasibility study of scanning RTA using a Xe arc lamp, Si wafers with various implanted species (P⁺, As⁺, B⁺ and BF₂⁺) and energies (1 keV–70 keV) were annealed under different scanning speeds and characterized for implant damage recovery, electrical activation and dopant diffusion. Sheet resistance and SIMS depth profiling measurement results successfully demonstrated the feasibility of the scanning RTA technique using a Xe arc lamp in semiconductor RTA processing applications. Electrical activation with desired levels of dopant diffusion can be achieved by optimizing process variables such as the lamp power, distance between the lamp and Si wafer, the area of light exposure, the scanning speed and possibly by preheating temperature.

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