Conventional methods of noncontact monitoring for as-implanted Si are Therma-Probe and Rutherford backscattering spectroscopy (RBS). Secondary ion mass spectroscopy (SIMS) and transmission electron microscopy (TEM) are also used for dose, depth profile, and implant damage characterization. After electrical activation by thermal treatment of implanted Si, sheet resistance (Rs) measurements using four point probes are mainly used for monitoring implanted dopant activation. However, the four point probes require physical contact and relatively large area (typically one or more orders of magnitude wider than the probe spacing) of uniform quality (poor spatial resolution) for meaningful measurements. SIMS, RBS and TEM are also used as complementary crystal quality and defect verification techniques after implanted dopant activation. However, the conventional characterization techniques often overlook problems due to their insensitivity to surface passivation quality, residual implant damage and defects.2–4 Development of a noncontact, high spatial resolution implant activation monitoring technique is desired. Photoluminescence (PL) from Si is a good candidate for this application.

Room temperature photoluminescence (RTPL) of crystalline Si, at wavelength $\sim$1.1 $\mu$m corresponding to interband transitions, is very sensitive to the density of non-radiative bulk and surface defects.5–11 This can be used as an indication of defect concentration in Si. Monitoring of surface defect formation during oxidation processes and minor carrier diffusion length of epitaxial Si by RTPL intensity has been reported previously.12–14 Promising results of spectroscopic RTPL studies on (ultra-) shallow implanted junctions and high energy low dose implanted junctions have also been reported previously.5,6,10–11 RTPL characterization of non-radiative defect density on surfaces and interfaces of Si with thin oxides have been studied.15–18 Metal contamination monitoring using spectroscopic RTPL has been reported previously.13 Plasma process induced damage (PPID) and plasma process chamber mismatch monitoring were also demonstrated using RTPL characterization of Si wafers.16–18

In this paper, RTPL was investigated as a potential noncontact electrical activation monitoring technique for implanted Si wafers. The major objectives were to understand the correlation between the degree of implant activation after RTA (determined by sheet resistance measurement and SIMS) and RTPL spectra/intensity for practical usage of the RTPL technique for noncontact electrical activation monitoring.

Experimental

Dual implanted Si wafers (phosphorous and boron) were prepared. Phosphorous ions (P$^+$ 1.0 MeV, 4.0 $\times$ 10$^{13}$ cm$^{-2}$) were implanted in p-Si(100) wafers for n-well formation. Boron ions (B$^+$ 10 keV, 3.0 $\times$ 10$^{14}$ cm$^{-2}$) were then implanted for p layer. The resistivity and background B concentration of p-Si(100) wafers were in the range of 20–30 $\Omega$ cm and 6–8 $\times$ 10$^{14}$ cm$^{-3}$, respectively. The P$^+$ implant for n-well formation resulted in the maximum P concentration of 3.5 $\times$ 10$^{15}$ cm$^{-3}$ at 1080 nm. The B$^+$ implant for p-layer formation resulted in the maximum B concentration of 3.4 $\times$ 10$^{19}$ cm$^{-3}$ at 44 nm. The usual dual implanted p-Si(100) wafers were annealed in the wide range of annealing conditions in a commercially available hot wall-based, rapid thermal annealing (RTA) system (WaferMasters SRFT-302LP) in 1 atm N$_2$ atmosphere.19,20 The annealing temperature was varied from 350 to 800 $^\circ$C and the annealing time was varied between 60 and 150 s. The annealing time in the hot wall-based RTA system was the wafer residence time in a preheated process chamber at programmed annealing temperature. This is different from the soak time typically referred to in lamp-based or wall RTA systems.21,22 Sheet resistance was measured after RTA under different conditions. SIMS P and B depth profiles were measured for selected wafers. RTPL spectra were measured from all wafers under two different excitation wavelengths (650 and 785 nm) for comparisons with the sheet resistance and SIMS P and B depth profiles after RTA under various conditions. A specially designed spectrograph for RTPL measurements (WaferMasters MPL-300), with a thermoelectrically cooled InGaAs linear diode array, was used. The RTPL spectra were measured in the wavelength range of 900–1400 nm. The excitation laser power at the wafer surface was in the range of 20–50 mW. The diameter of the focused excitation laser beam on the wafer was approximately 50 $\mu$m.

Results and Discussion

Figure 1 shows a schematic cross-section of dual implanted (P$^+$ 1.0 MeV, 4.0 $\times$ 10$^{13}$ cm$^{-2}$ + B$^+$ 10 keV, 3.0 $\times$ 10$^{14}$ cm$^{-2}$) Si. The probing depths of RTPL under 650 and 785 nm excitation and the sheet resistance measurement locations were illustrated. SIMS P and B profiles after annealing under the annealing conditions which resulted in minimum and maximum dopant diffusion, are plotted with background B doping concentration of the P$^+$-Si(100) wafers. No B and P diffusion was observed after 350 $^\circ$C annealing for 60 s (B and P profiles in blue color). The maximum B and P diffusion were measured at 800 C for 150 s (B and P profiles in red color). A small amount of transient enhanced diffusion (TED) of B was observed as the annealing temperature was increased above 600 C. The P profile did not change significantly compared to B even after the 800 C, 150 s anneal. This is due to the combination of difference in diffusivity and solid solubility of B and P in Si. Since the maximum concentration of B (3.2 $\times$ 10$^{17}$ cm$^{-3}$) is two orders of magnitude higher than that for P (3.4 $\times$ 10$^{17}$ cm$^{-3}$), the driving force for B diffusion is higher than that for P, under the same annealing temperature and time. End-of-range (EOR) damage from B ion implantation and pre-existing P implant...
damage in the Si lattice also plays an important role for TED. Larger B diffusion compared to P diffusion is expected and was experimentally verified by the SIMS analysis.

Sheet resistance of dual implanted \((P^+ 1.0 \text{ MeV}, 4.0 \times 10^{13} \text{ cm}^{-2} + B^+ 10 \text{ keV}, 3.0 \times 10^{14} \text{ cm}^{-2})\) Si wafers was measured after annealing. The measured sheet resistance values of the dual implanted wafers annealed in the wide range of annealing temperature (350–800 °C) and time (75–150 s) were plotted in Fig. 2. The sheet resistance was in the range of few hundred Ω/sq. after 350 °C annealing regardless of annealing time. As the annealing temperature increases, the sheet resistance rapidly increases up to \(\sim 7000 \text{ Ω/sq.}\) and decreases down to a plateau of \(\sim 2500 \text{ Ω/sq.}\) before approaching \(\sim 1000 \text{ Ω/sq.}\) around 800 °C. The sheet resistance maxima occurred at different annealing temperatures, depending on the annealing time. The shorter annealing time resulted in higher annealing temperature for the sheet resistance maxima. For 75 s annealing, the sheet resistance maxima occurred at 590 °C. For 90 s, 120 s and 150 s annealing, the sheet resistance maxima occurred at 560, 500 and 450 °C, respectively.

The low sheet resistance (few hundred Ω/sq.) after annealing at 350 °C is the result of measuring B-doped \(p^+\)-Si(100) wafer through the dual implanted layers. The dotted lines up to the sheet resistance maxima indicates the progress of n-well formation by electrical activation of implanted \(P^+\) in B-doped \(p^-\)-Si(100) wafers. The completion of n-well formations occur at the annealing temperature for the sheet resistance maxima for a given annealing time. At this temperature, the electrical activation of \(B^+\) for p-layer was not sufficient. The annealing temperature regions of solid lines, from \(\sim 7000\) to \(\sim 2500 \text{ Ω/sq.}\), indicate the degree of implanted \(B^+\) in the p-layer. The sheet resistance is quite high because only the insufficiently activated shallow (240–400 nm) p-layer, with lower B concentration \((<3.4 \times 10^{19} \text{ cm}^{-3})\), contributes to the reduction of sheet resistance. The p-layer is electrically isolated from the n-well by pn junctions. As the degree of electrical activation of implanted \(B^+\) increased, the sheet resistance rapidly decreased down to \(\sim 2500 \text{ Ω/sq.}\) as the annealing temperature increased. The sheet resistance starts to decrease again at 700 °C due to the p-layer thickening, by B diffusion into the N well region. As seen from the SIMS B depth profile (red solid line) in Fig. 1, high temperature anneal enhanced B diffusion and pushed the pn junction deeper into the N well. Even though the pn junction cannot be formed by 60 s annealing at 350 °C, the depth of equal B and P concentration was \(\sim 240 \text{ nm}\) from the surface. After 150 s annealing at 800 °C, the depth of equal B and P concentration (junction depth assuming the same activation rate for B and P) became \(\sim 400 \text{ nm}\). B also diffused into the B-doped \(p^-\)-Si(100) wafer under high temperature annealing. This should not affect the sheet resistance measurement from the surface because the pn junction between the top \(B^+\) implanted p-layer and \(P^+\) implanted n-well electrically isolate the B-doped \(p^-\)-Si(100) wafer. The B-doped \(p^-\)-Si(100) wafer should be invisible during the

**Figure 1.** (a) Schematic cross-section of dual implanted \((P^+ 1.0 \text{ MeV}, 4.0 \times 10^{13} \text{ cm}^{-2} + B^+ 10 \text{ keV}, 3.0 \times 10^{14} \text{ cm}^{-2})\) Si with RTPL probing depths and (b) SIMS P and B profiles after annealing under various annealing conditions.

**Figure 2.** Sheet resistance of dual implanted \((P^+ 1.0 \text{ MeV}, 4.0 \times 10^{13} \text{ cm}^{-2} + B^+ 10 \text{ keV}, 3.0 \times 10^{14} \text{ cm}^{-2})\) Si after annealing in the wide range of annealing temperature (350–800 °C) and time (75–150 s).
sheet resistance measurement from the surface through the implanted pn junction on the p$^-$Si(100) wafer.

All reactions, electrical activation and diffusion of implanted B and P atoms, compete at different rates during annealing. The maximum concentration of P in the n-well region is $3.5 \times 10^{17}$ cm$^{-3}$ and is almost two orders of magnitude smaller than the B concentration ($3.4 \times 10^{19}$ cm$^{-3}$) of top B$^+$ implanted p-layer. The implantation induced Si lattice damage should be much smaller than that of P$^+$ implanted n-well compared to the dual (P$^+$ and B$^+$) implanted top p-layer. Thus, the electrical activation of P atoms in the n-well should require less thermal energy for P atoms engaging into the Si lattice for electrical activation compared to the thermal energy for B atoms to find substitutional sites for electrical activation. It is reasonable to assume that the P activation in the n-well region took place at faster rates at low temperatures (for either the entire annealing time under low annealing temperatures or during rising temperature under high annealing temperatures) and the B activation in the top p-layer took place at slower rates.

Multiwavelength RTPL measurements were done for all wafers to gain insight into dopant activation mechanisms during thermal annealing. RTPL measurements should be able to reveal the effects of thermal annealing on the sheet resistance values (few hundreds to 7000 Ω·sq.) and residual implant damage after annealing under different conditions. Since the efficiency of the interband RTPL is limited by the density and location of non-radiative bulk and surface defects, we should look at broad RTPL spectra in the entire wavelength range (900–1400 nm), representing lattice defects, more closely. Multiwavelength RTPL with different penetration depths can provide a general idea on the locations of non-radiative defects and recombination centers with respect to the wafer surface. RTPL penetration depths of the two excitation wavelengths (650 and 785 nm), relative to the junction depths of ~300 nm and ~2500 nm, were illustrated as part of Fig. 1. The penetration depth is defined as the depth at which the intensity of the excitation wavelength in Si falls to 1/e (about 37%) of its original value, just beneath the surface. It should be noted that the RTPL signal can be emitted anywhere where photo-excited free carriers (electrons and holes) meet recombination partners. In blanket Si wafers, RTPL measurement from the one side of the wafer can detect the anomalies on the other side of wafer, which is 775 μm away.

Figures 3a~3d show RTPL spectra of wafers annealed in the temperature range of 350–800°C for 75 s and 150 s in the wavelength range of 900–1400 nm, under 650 and 785 nm excitation. Note that the vertical scales of RTPL intensity axes are different. For easy spectra and intensity comparisons, within data sets, the vertical scales were changed to the nearest thousand counts. Figures 4a~4d show superimposed RTPL spectra of Figs. 3a~3d for easy comparison. The RTPL and SIMS data showed no change between the as implanted wafer and wafers annealed at 350°C. Thus, the RTPL and SIMS data can be used as a reference for comparing residual damage after annealing at high temperatures.

In general, the RTPL intensity of 785 nm excitation is stronger than that of 650 nm excitation and the RTPL intensity from 150 s annealed wafers was stronger than that from 75 s annealed wafers. The RTPL intensity generally increases with the increase of annealing temperature and time, regardless of excitation wavelength, indicating the density of defects are decreasing with increase annealing temperature and time. RTPL spectra are generally broader under 650 nm excitation than under 785 nm indicating the defect states are near the surface.

The interband RTPL of crystalline Si near 1.1 μm (more precisely ~1140 nm) is very sensitive to the density of non-radiative bulk and surface defects. Interband RTPL has also been used in monitoring; surface and interface defects during oxidation, epitaxial Si quality, electrical activation of implanted Si after RTA, metal contamination, ultraviolet (UV) radiation damage of SiO$_2$/Si interface and PPID. However, it serves as an indirect indication of density of defects. Photo-excited free carriers can easily be captured by defects (non-radiative recombination centers). As a result, the lifetime of free carriers is very short and the free carriers cannot travel long distances to recombine with the opposite carriers for radiation recombination (PL). Consequently, the RTPL intensity, in particular the interband (band edge) RTPL near 1140 nm, becomes very weak in Si with (electrically active) defects. We should be able to see the direct evidence of implanted lattice damage by RTPL, other than the band edge RTPL, if the non-radiative recombination centers dominate

![Figure 3](https://example.com/figure3.png)

Figure 3. 650 nm and 785 nm excited RTPL spectra of dual implanted (P$^+$ 1.0 MeV, $4.0 \times 10^{13}$ cm$^{-2}$ + B$^+$ 10 keV, $3.0 \times 10^{14}$ cm$^{-2}$) Si after annealing in the wide range of annealing temperature (350–800°C) for 75 s (a) and (b) and 150 s (c) and (d).
Annealing Time: 75s

Figure 4. 650 nm and 785 nm excited superimposed RTPL spectra of dual implanted (P\textsuperscript{+}, 1.0 MeV, 4.0 \times 10\textsuperscript{13} cm\textsuperscript{-2} + B\textsuperscript{+}, 10 keV, 3.0 \times 10\textsuperscript{14} cm\textsuperscript{-2}) Si after annealing in the wide range of annealing temperature (350–800°C) for 75 s ((a) and (b)) and 150 s ((c) and (d)).

The recombination process in implanted Si with insufficient annealing for implantation-induced lattice damage recovery and electrical activation of implanted species. In earlier RTPL studies of implanted Si after RTA, the annealing temperatures are generally 800°C or higher and did not observe direct evidence of the effect of lattice damage on the RTPL spectra because the band edge RTPL dominates the spectra.\textsuperscript{3,3-5,8-11}

Figure 3a shows 650 nm excited RTPL spectra from the 75 s annealed wafers at temperatures between 350°C and 800°C. The penetration depth of 650 nm excitation laser is estimated to be ∼4 μm. Very broad and weak RTPL spectra in the wavelength range of 900–1400 nm were measured from the 75 s annealed wafers between 350 and 580°C. No RTPL peaks peculiar to the Si crystal at ∼1140 nm (band edge RTPL peak) were noticeable. Only band tail RTPL spectra (broad and weak RTPL spectra from 900–1400 nm) were observed. As the annealing temperature is increased from 590°C to 800°C, the band edge RTPL starts to take place and dominate the RTPL spectra. The appearance of a band edge RTPL peak at ∼1140 nm coincided with the annealing temperature for the sheet resistance maximum at 75 s annealing. Significant progress of annealing (lattice damage recovery and dopant activation) in the P\textsuperscript{+} implanted n-well region is expected in the temperature range above 590°C from the sheet resistance and RTPL spectra measurements.

RTPL spectra from the same set of wafers under 785 nm excitation with a deeper penetration depth of ∼8 μm are shown in Fig. 3b. Since the 785 nm excitation for RTPL measurements can reach the B-doped p–Si(100) wafer through the dual implanted layers, all wafers showed the band edge RTPL peak form crystalline Si (Eg = 1.12 eV at RT), regardless of annealing temperature. Noticeable increase of RTPL intensity was also measured at 590°C. The rate of band edge RTPL intensity increase with annealing temperature between 590°C and 720°C was higher than that under 650 nm excitation. This is due to the crystallinity improvement near the interface of the P\textsuperscript{+} implanted n-well region and the B-doped p–Si(100) wafer.

Figures 3c and 3d show 650 nm and 785 nm excited RTPL spectra from the set of wafers annealed for 150 s at temperatures between 350°C and 800°C. The trends are the same as for the 75 s annealed wafers. However, the temperature for the appearing the band edge RTPL peak was lowered to 450°C at which the sheet resistance reached the maximum value. The rate of band edge RTPL peak intensity increase from 450°C to 800°C was gradual, as expected from the gradual decrease of the sheet resistance in Fig. 2. Longer (150 s) annealing resulted in stronger higher band edge RTPL intensity than shorter annealing (75 s) under a given annealing temperature. This is well within expectations.

The long time anneal at high temperature resulted in B and P diffusion as seen in a part of Fig. 1. It moves the top pn junction slightly deeper and reduces the sheet resistance, as seen in Fig. 2. It would also significantly reduce residual implantation-induced lattice damage. As a result, the band edge RTPL intensity is further increased in wafers annealed at high temperatures, regardless of annealing time.

Summary

The spectral distribution and intensity of RTPL signal (band edge and band tail RTPL peaks) from implanted Si showed excellent correlation with the sheet resistance measurement values. Considering the advantages of RTPL characterization techniques (noncontact nature, high spatial resolution and virtual depth profiling capability), RTPL spectra/intensity can be used for practical noncontact electrical activation and residual implantation-induced residual damage monitoring after annealing. It can also be used for non-contact, in-line monitoring of passivation, dielectrics/semiconductor interface, junction integrity and PPID as reported previously.\textsuperscript{2,5,9,11,13-18} Even though Si is an
indirect bandgap material and RTPL cannot provide detailed identification of dopants due to the broadened spectra at room temperature, it can offer very insightful information about how Si would behave under the presence of excess electronic carriers, somewhat similar to the device operating conditions under electrical bias. The usage of the RTPL technique as a noncontact, in-line monitoring application would be very beneficial for process development, material characterization and quality control.

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