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Very High Magnification Optical Characterization of Global and Local Distortion of Si Wafers after Laser Spike Annealing

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Abstract- The understanding of macro- and micro-scale wafer shape changes during device fabrication process steps is becoming very critical in developing and optimizing advanced technology node devices in which new materials such as Ni, NiPt and/or Ge are introduced. We have developed a non-contact, in-line process and/or material property monitoring method which uses various forms (reflection, diffraction, interference and scattering) of interactions between semiconductor wafers and a laser beam. Laser spike anneal (LSA) induced changes of surface profiles in TiN/NiPt/$Si_{1-x}Ge_x$/Si (100) and $Si_{1-x}Ge_x$/Si (100) wafers are characterized using the newly developed very high magnification optical surface profilometry (OSP-300) system. Significant global and local changes of wafer surface profiles were observed after LSA. Multi-wavelength micro-Raman studies revealed significant changes in Ge content and lattice level stress in $Si_{1-x}Ge_x$/Si (100) wafers annealed under various LSA temperatures and dwell times.

I. INTRODUCTION

The importance of understanding process induced deformations and stresses at the wafer level, die level, micro-area level and device level is becoming compelling in developing high performance, advanced technology node devices [1-5]. An element of large atomic size, Ge, is intentionally introduced to create lattice strain in Si up to ~35atm% for carrier mobility enhancement [6-9]. The introduction of new materials and miniaturization of devices induces a high level of deformation and stress.

A wafer always experiences global and local (macro and micro) surface profile and strain (or stress) changes during various process steps due to chemical reactions and physical changes under a specific (either uniform or non-uniform) process environment. In-line process monitoring has been playing a vital role in quickly identifying and resolving equipment and/or process problems which affect device yield in semiconductor manufacturing environments [1, 2].

Wafer level global flatness is strongly desired for preventing pattern overlay problems in photolithography steps [1, 10]. In the case of $Si_{1-x}Ge_x$/Si, intentional local strain generation is introduced for enhancing device performance by adding tens of atomic percent of Ge in Si [6-9]. Process induced deformation of surface flatness and/or local strain can cause focusing problems in photolithography steps and results in pattern overlay problems and critical dimension errors in nanometer scale devices [1, 10]. Characterizing, understanding and managing process induced surface profiles and lattice strains are as important as process control for nanometer scale device manufacturing.

Recently, the coherent gradient sensing (CGS) interferometer has been introduced as a wafer bow and warpage monitoring instrument and its applications in blanket and patterned wafer characterization between process steps have been introduced [3-5, 10-12]. Since the CGS technique utilizes an entire wafer image captured by a 1024x1024 CCD array and interference fringes for analysis, it has limited spatial resolution (>300μm) and height resolution (~1/10 wavelength at best) [12]. For proper characterization of wafers in advanced device fabrication process steps, sub-micron spatial resolution and sub-nanometer height resolution are required. We have developed a laser-based optical surface profilometry (OSP-300) system to realize the sub-micron spatial resolution and sub-nanometer height resolution required for advanced semiconductor device research and development [13, 14].

In this paper, process induced surface profiles in TiN/NiPt/$Si_{1-x}Ge_x$/Si (100) and $Si_{1-x}Ge_x$/Si (100) wafers are characterized before and after laser spike anneal (LSA) using the newly developed very high magnification optical surface profilometry (OSP-300) system. In addition, the distribution of lattice stress/strain, Ge content and crystallinity in the depth direction were measured using a multi-wavelength micro-Raman spectroscopy (MRS-300) system.

II. EXPERIMENT

A. Optical Surface Profilometry

Optical wafer surface profiling techniques, using laser beam reflection from the wafer surface, have been widely used in the semiconductor industry for rough inspection of wafer flatness, wafer bow and process induced stress after film deposition on blanket wafers. Due to the optical sensing, wafer holding and wafer rotation/translation

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methods used in the system, fine measurement in the sub-micron range and precise pattern wafer inspection are not possible using conventional inspection systems.

To overcome the difficulties of conventional optical reflection techniques (i.e., sub-micron level fine measurement and pattern wafer inspection capabilities), a new optical surface profilometry system has been developed [13, 14]. Figure 1 illustrates the primary components of the OSP-300 system. The system irradiates a wafer with a laser beam at a fixed incident angle and captures reflected, diffracted and scattered images from the wafer to characterize the wafer surface profile and pattern distortions. The system generates wafer maps of vector plot, grid plot, intensity, height contours, distortion and three dimensional (3D) surface profiles. It also generates the height profile and estimated curvature along the major crystal orientations, as well as a histogram of wafer surface mis-orientation from the wafer stage. Process induced surface profiles can be estimated by comparing wafer surface profiles before and after a process step or a series of process steps in both blanket and patterned production wafers. Wafer maps of the accumulated impact of these process steps on the wafer's surface profile can be generated. The OSP-300 system has achieved both sub-micron spatial resolution and sub-nanometer height resolution (from blanket and patterned wafers) required for advanced semiconductor device research and development.

For very high magnification surface characterization, such as surface roughness measurements, an atomic force microscope (AFM) is often used. In an AFM, a constant force is maintained between the probe and sample by measuring the force with a "cantilever" (or light lever) sensor and using a feedback control electronic circuit to control the position of the Z-axis piezoelectric positioning device. The motion of the probe over the surface is generated by piezoelectric positioning devices that move the probe and force sensor across the surface in the X and Y directions [15]. The probe is raster scanned across the surface of a very limited area (typically few mm^2). By monitoring the motion of the probe as it is scanned across the surface, a three dimensional image of the surface is constructed.

The operating principles of the OSP-300 and AFM are very similar. The OSP-300 is designed to characterize the surface profiles of full size wafers (up to 300mm in diameter) with very high magnification (sub-nanometer height resolution) and high spatial (sub-micron) resolution, while the AFM focuses on very high magnification (sub-nanometer) surface characterization of a very small area using the light lever (cantilever). The sub-nanometer height resolution and sub-micron spatial resolution of the OSP-300 system were achieved by using appropriate optical magnification and stage resolution. Full wafer surface characterization with AFM-equivalent resolution is realized by the OSP-300 system.

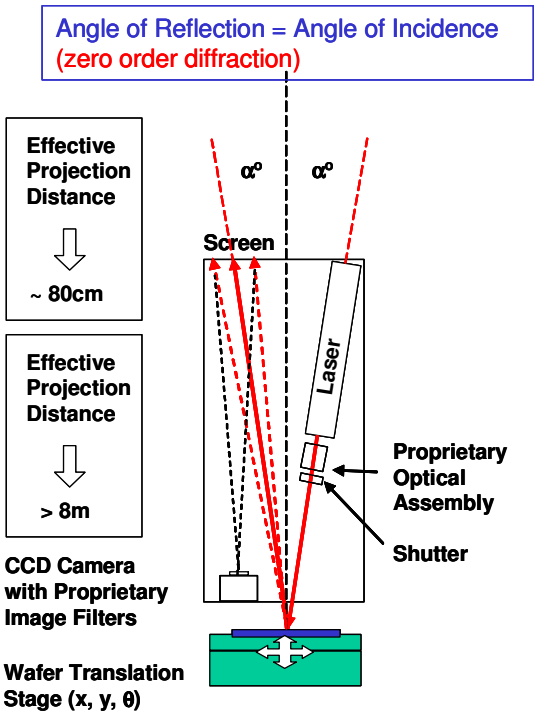

Fig. 1. Schematic illustration of the primary components of optical surface profilometry (OSP-300) system.

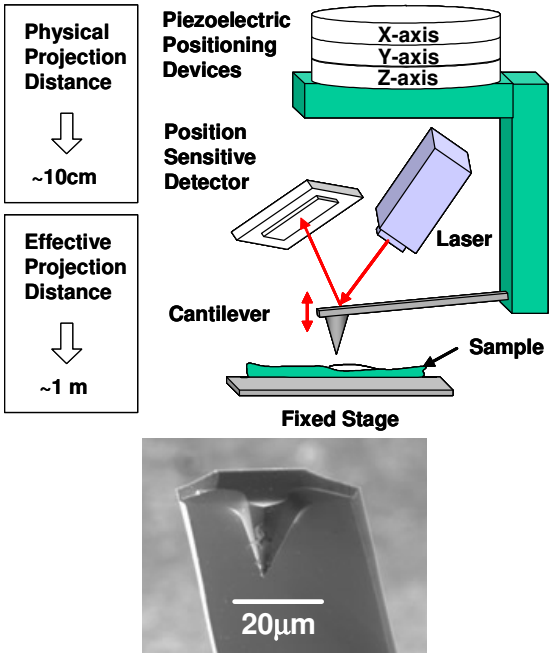

Fig. 2. Schematic illustration of the primary components of an atomic force microscopy (AFM) system. This figure illustrates the similar operating principles of the AFM and OSP-300 system.

B. Interpretation of OSP-300 Measurement Data

The Optical Surface Profilometry system (OSP-300) irradiates a wafer with a laser beam at a fixed incident angle and captures reflected, diffracted, and scattered images from the wafer to characterize the wafer surface profile and pattern distortions [13,14]. Graphical representations of surface profiles from blanket wafers, measured by the OSP-300 system, are shown in Fig. 3. Grid plots, vector plots, intensity plots, height maps, beam position distribution plots, curvature plots along major crystal axes and 3D plots can be obtained from a single measurement. It also generates the height profile and estimated curvature along the major crystal axes, as well as a histogram of wafer surface mis-orientation from the wafer stage. By comparing wafer surface profiles before and after a certain process step or a series of process steps, process induced surface profiles and the accumulated impact of these process steps on the wafer's surface can be estimated and displayed as wafer maps.

The grid plot, vector plot and 3D contour maps provide visual images of global and local surface distortions. The intensity plot provides an indication of the direction of distortion (either concave or convex). The height profile, beam position distribution with histogram, curvature and height range along major crystalline axes offers a very powerful tool for statistic process control (SPC) and valuable hints for process and/or equipment related problem diagnosis.

C. Sample Preparation

Blanket Si wafers were prepared and their surface profiles were measured as a reference. A number of TiN/NiPt/$Si_{1-x}Ge_x$/Si (100) and $Si_{1-x}Ge_x$/Si (100) wafers were prepared. TiN/NiPt/$Si_{1-x}Ge_x$/Si (100) wafers were annealed by either a conventional lamp-based rapid thermal processing (RTP) system or a laser spike annealing (LSA) system using 10.6μm laser beam. A large number of $Si_{1-x}Ge_x$/Si (100) wafers with various Ge content and $Si_{1-x}Ge_x$ layer thickness were prepared. The $Si_{1-x}Ge_x$/Si (100) wafers were annealed by LSA at various target wafer temperatures and dwell times to investigate the effect of target annealing temperature at a given dwell time and the effect of dwell time at a given target annealing temperature.

D. Sample Characterization

The surface profile measurement was performed on various types of wafers, with or without thermal treatment, using the newly developed very high magnification, optical surface profilometry system (OSP-300).

For $Si_{1-x}Ge_x$/Si (100) wafers, additional characterization was performed using the WaferMasters' Multi-Wavelength Micro-Raman Spectroscopy (MRS-300) system of Ge content and lattice level stress for various LSA temperatures and dwell times. The details of the MRS-300 system and its applications can be found in previous reports [16, 17].

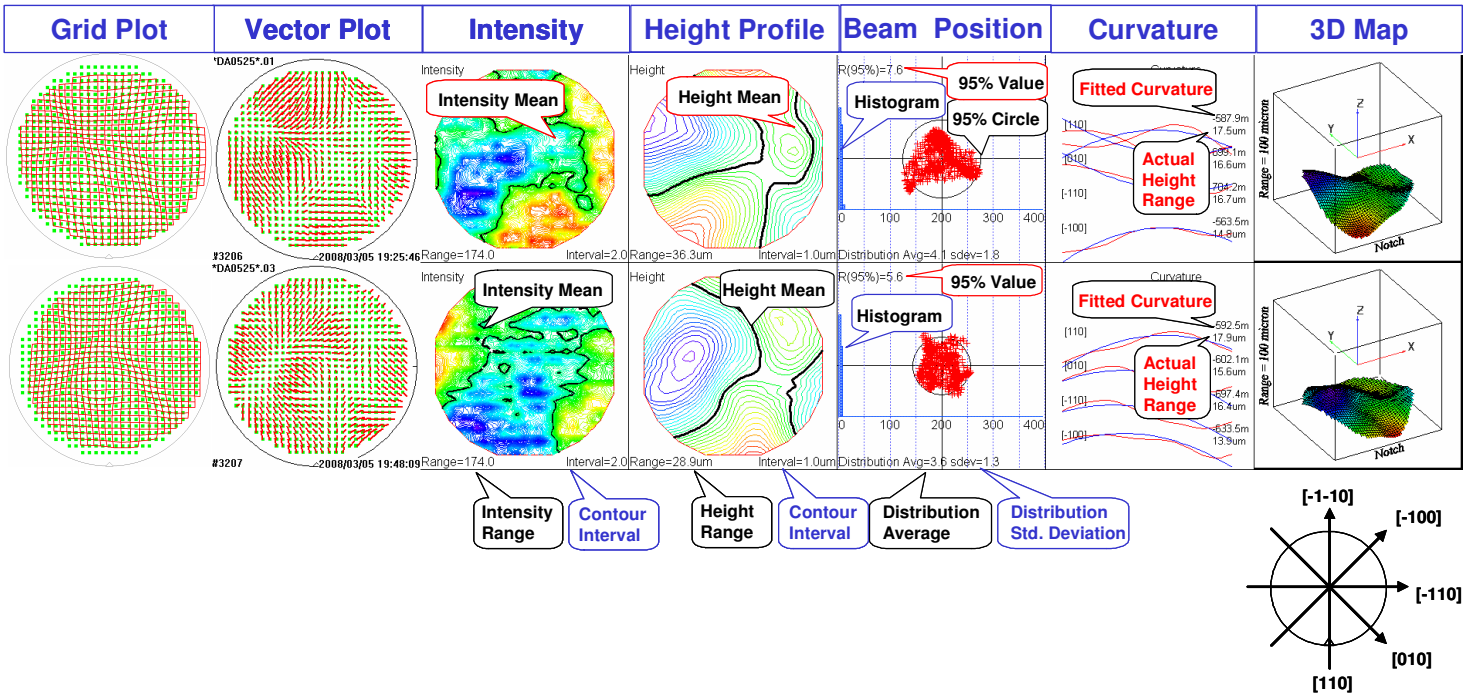

Fig. 3. Graphical representation of surface profiles measured from two blanket Si wafers by the OSP-300 system.

III. RESULTS AND DISCUSSIONS

A. Blanket Si Wafers

As seen in Fig. 3, although it may look perfect, a commercially available 300mm Si wafer has significant localized surface distortions. We have seen a wide range of variations, depending on wafer grade and suppliers. Measurement repeatability of the OSP-300 system was verified. Since the system is extremely sensitive to the slope change of a measurement spot, the existence of small particles, in the range of 1µm, can generate global gravitational wafer deformation (sagging) and completely different surface profiling results. Inspection of incoming wafers can be as important as process and equipment monitoring.

B. TiN/NiPt/$Si_{1-x}Ge_x$/SiWafers

TiN/NiPt/$Si_{1-x}Ge_x$/Si (100) and $Si_{1-x}Ge_x$/Si (100) wafers were annealed using either a conventional lamp-based RTP system or an infrared (IR, λ=10.6µm) LSA system [10]. Figure 4 shows wafer surface profiles of three wafers after annealing. The first two wafers were annealed using the lamp-based RTP system at the same temperature and pyrometer reading. For a wafer with a thin $Si_{1-x}Ge_x$ layer (40nm), the wafer surface was relatively flat, even after the RTP step. In contrast, for the wafer with a thick $Si_{1-x}Ge_x$ layer (120nm), the wafer surface was heavily distorted after the RTP step and took on a bowl shape. The height ranges of the two wafers were 12.0µm and 32.5µm, respectively. The IR laser annealed wafer became distorted and took on a saddle shape. The height range was measured as 554.1µm (~0.55mm). This level of wafer bowing and distortion can cause severe pattern overlay problems during photolithography steps, even with vacuum chucking of wafer. The LSA annealed wafer had a slightly thicker $Si_{1-x}Ge_x$ layer (160nm), but the 40nm thickness difference in the $Si_{1-x}Ge_x$ layer is not believed to cause both bowing magnitude and direction.

We believe that both $Si_{1-x}Ge_x$ layer thickness (optical property difference) and photon energy distribution of both lamp-based RTP and IR LSA-based systems impact wafer shape after annealing. The raster scan of LSA on a wafer might be the origin of the saddle shaped wafer bowing.

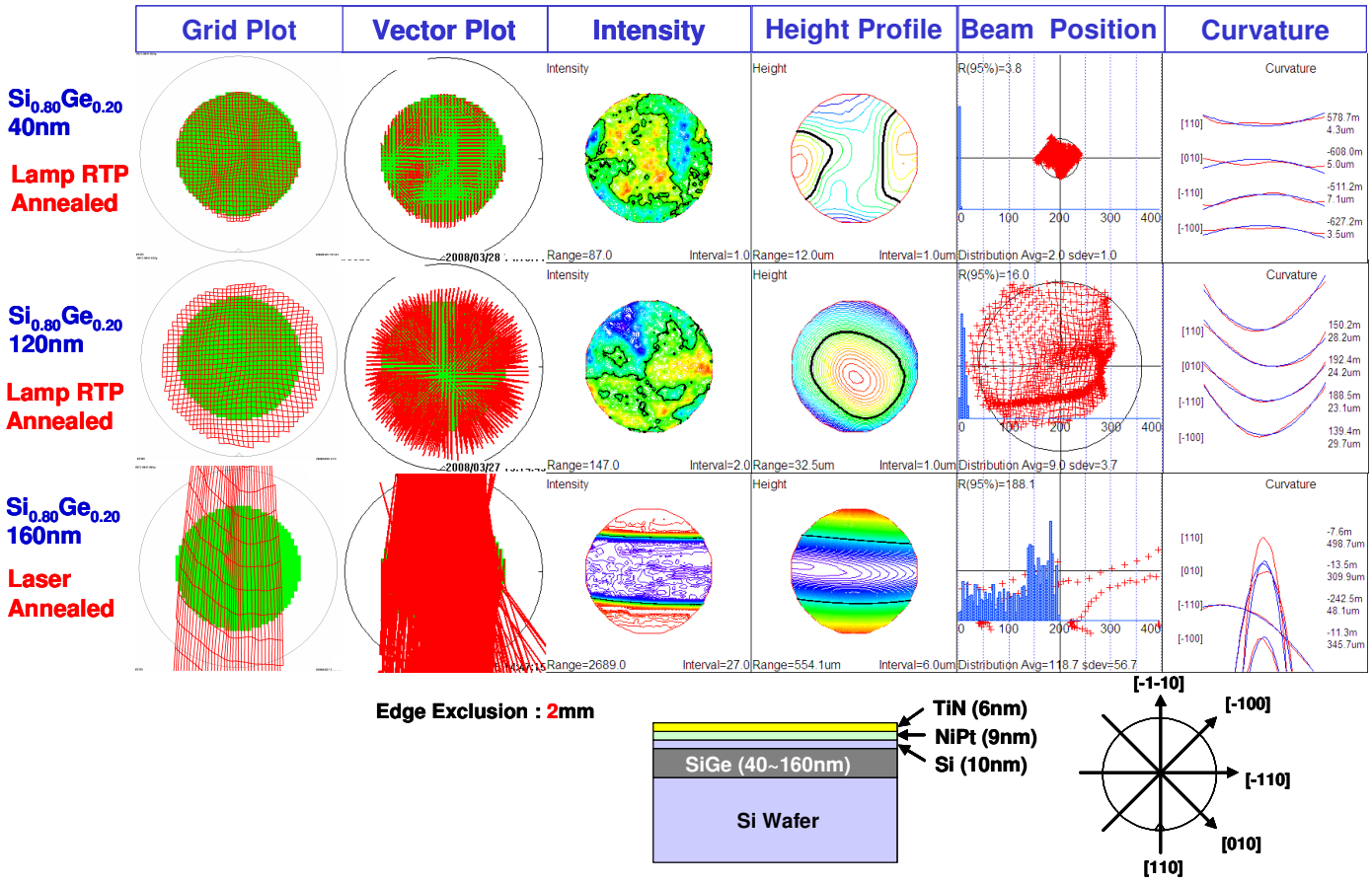

Fig. 4. OSP-300 measurement summary of TiN/NiPt/$Si_{1-x}Ge_x$/Si (100) wafers after lamp-based RTP anneal and LSA.

C. $Si_{1-x}Ge_x$/SiWafers – Characterization by OSP-300

A large number of $Si_{1-x}Ge_x$/Si (100) wafers with various Ge content and B dopant levels were prepared and characterized by their surface profile changes before and after LSA. The thickness of $Si_{1-x}Ge_x$/Si layer varied from 40nm to 160nm. Figure 5 shows a few sample characterization results of $Si_{1-x}Ge_x$/Si (100) wafers with various Ge content before and after LSA. Due to space limitations, OSP characterization results from B doped wafers and wafers with $Si_{1-x}Ge_x$/Si layer thickness other than ~60nm, are not shown.

As seen in the Fig. 5, before LSA, all wafers showed fairly symmetrical convex shapes. The $Si_{1-x}Ge_x$/Si (100) wafer with a Ge content of 20% showed the largest wafer bow (the smallest curvature) and the largest height range (81.6µm). As Ge content increases, the height range gradually decreases to 30.1µm at 28% of Ge and to 25.9µm at 32% of Ge. The shape of all wafers moved towards concave tendencies after LSA. The wafer with 20% Ge content remained convex after LSA, but the curvature was significantly increased (the wafer became flatter) after LSA. The wafers with Ge content of 28% and 32% took on an inverted saddle shape after LSA. The effect of wafer shape change and stress change after annealing can easily be recognized from the grid plots, vector plots, height profiles, curvature plots and 3D maps. The shape change and local distortion can easily be quantified from the height profiles, beam position distribution plots, histograms, curvature plots and 3D maps. These intuitive and quantitative characterization methods can provide extremely valuable guidance to process optimization and troubleshooting during process development and manufacturing phases.

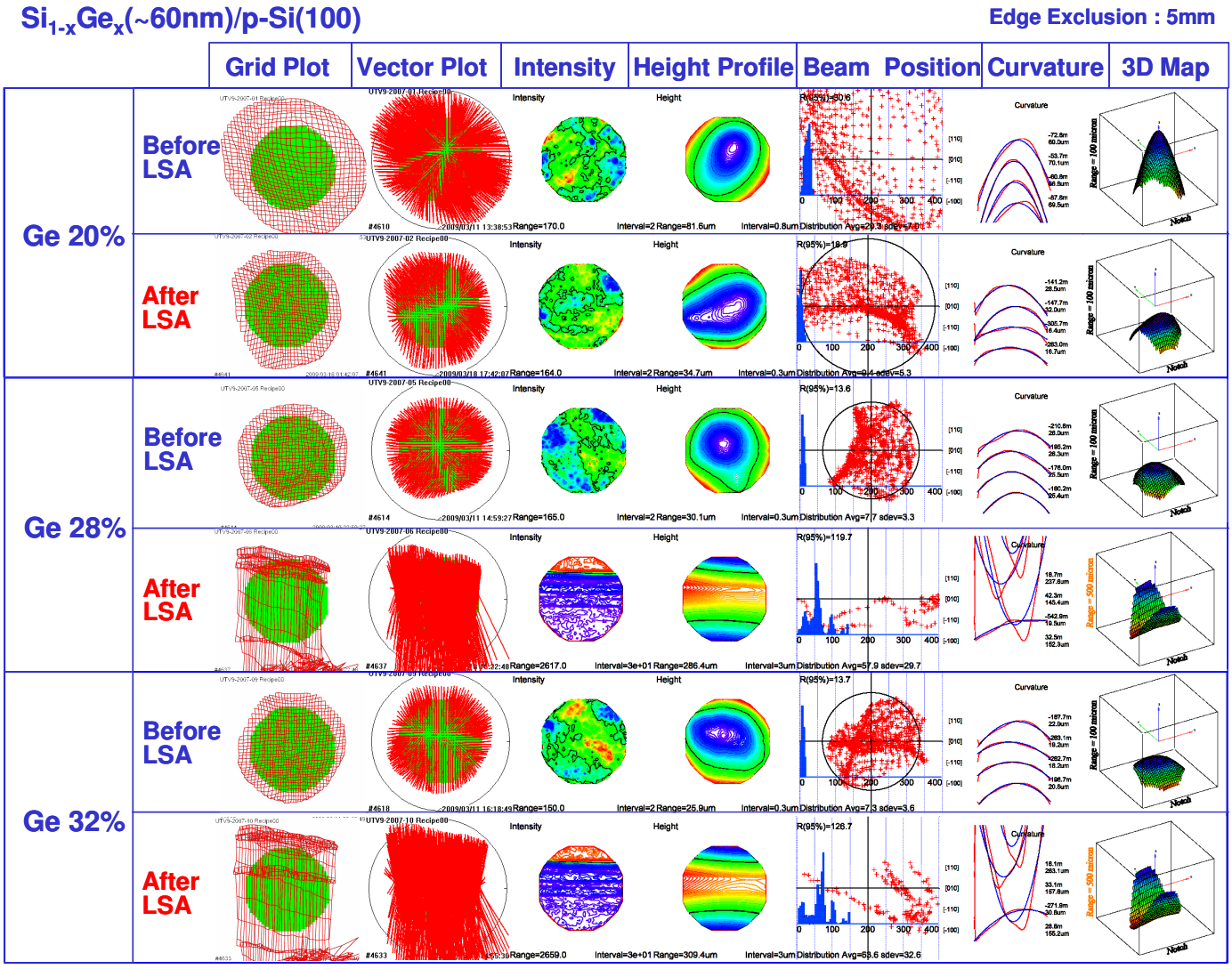

Fig. 5. OSP-300 measurement summary of $Si_{1-x}Ge_x$/Si (100) wafers with various Ge content before and after LSA.

D. $Si_{1-x}Ge_x$/SiWafers – Characterization by MRS-300

Additional characterization of Ge content and lattice level stress in the $Si_{1-x}Ge_x$/Si (100) wafers with various Ge content was performed using the WaferMasters' Multi-Wavelength Micro-Raman spectroscopy (MRS-300) system after various LSA temperatures and dwell times. Details of Ge content and stress/strain characterization using Raman spectroscopy can be found elsewhere [6-9, 17].

To investigate the effect of target annealing temperature at a given dwell time and the effect of dwell time at a given target annealing temperature, a large number of $Si_{1-x}Ge_x$/Si (100) wafers, with various Ge content and $Si_{1-x}Ge_x$ layer thickness, were prepared and annealed by LSA at various target wafer temperatures and dwell times.

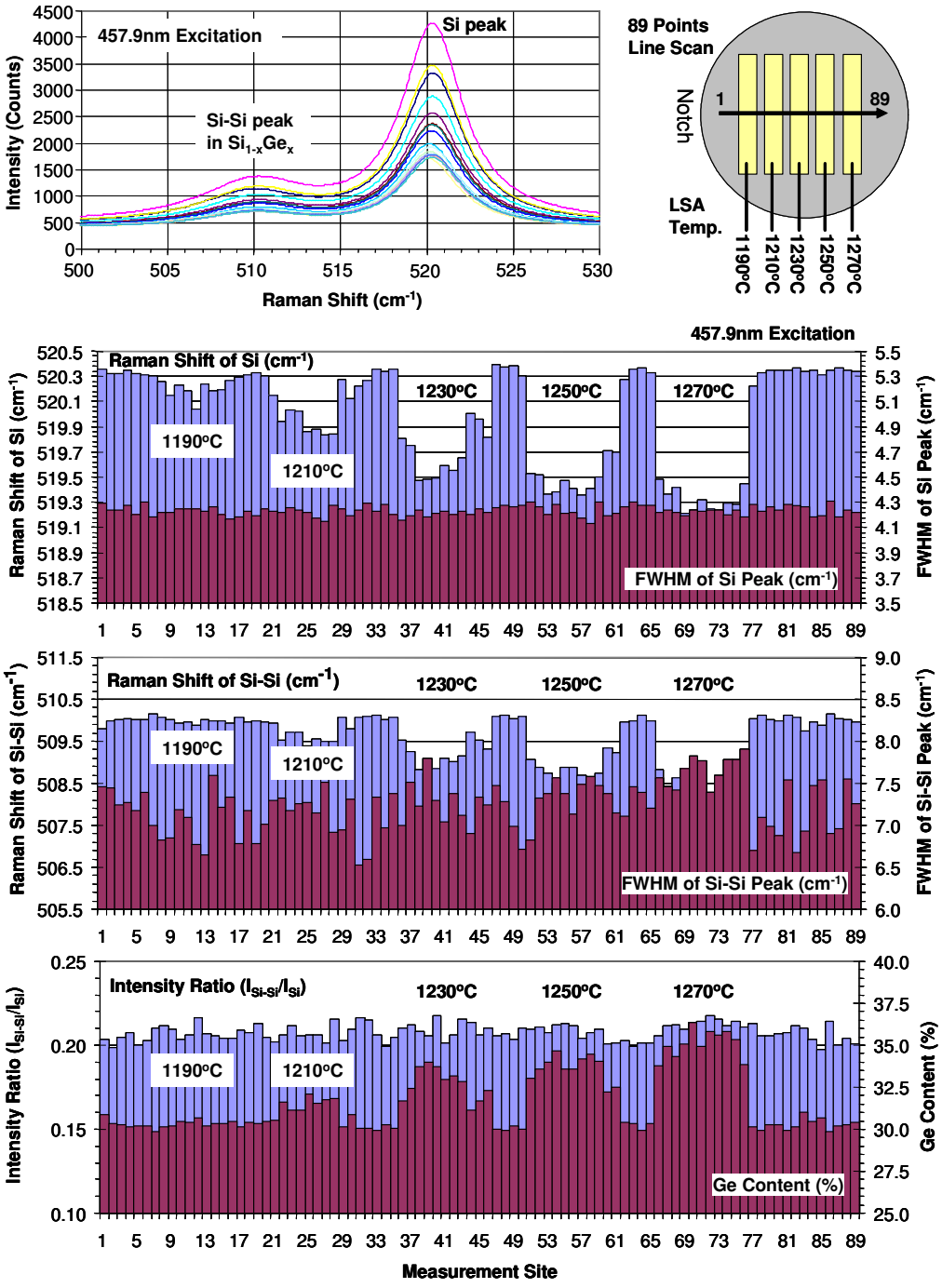

Fig. 6. Line scan Raman measurement results from $Si_{0.72}Ge_{0.28}$/Si (100) wafers annealed at 5 different LSA temperatures.

Figure 6 shows 89 point line-scan Raman measurement results corresponding to the 5 different annealing zones. Raman signals from three excitation wavelengths (457.9nm, 488.0nm and 514.5nm), which have different penetration depths, were measured using an MRS-300 system. Due to space limitations, only 457.9nm excitation Raman measurement results are shown. The Raman shift of the un-annealed region was measured at 520.3cm^{-1} indicating that the Si substrate is nearly stress free. As annealing temperature increases, both the Raman shift of Si and Si-Si in $Si_{1-x}Ge_x$ shifted to the lower wavenumber side. This suggests that the tensile stress in the Si substrate increases as the LSA temperature increases. While the full-width-at-half-maximum (FWHM) of Raman signal of Si remained unchanged, the FWHM of the Raman signal and Si-Si in $Si_{1-x}Ge_x$ fluctuated as the LSA temperature was increased. This indicates crystallinity of the top $Si_{1-x}Ge_x$ layer was largely influenced by LSA temperature. The intensity ratio of I_{Si-Si}/I_{Si} remained reasonably constant indicating the $Si_{1-x}Ge_x$ layer thickness did not change much after the LSA. However, Ge content in the top $Si_{1-x}Ge_x$ layer increased as the LSA temperature was increased. This strongly suggests Ge concentration increase by some sort of Ge segregation or precipitation in the top $Si_{1-x}Ge_x$ layer or $Si_{1-x}Ge_x$/Si (100) interface. Details of Raman data analysis and interpretation of $Si_{1-x}Ge_x$/Si can be found in other literatures [6-9, 17].

E. Discussions

Both the OSP-300 and MRS-300 system can provide information on wafer stress. The OSP-300 system, which mainly uses a reflected laser beam, can detect physical change or deformation of the wafer surface with very high magnification. The MRS-300 system, which detects inelastic light scattering (Raman scattering) from probed materials, can provide lattice level stress/strain and chemical composition information. The surface flatness and lattice level stress/strain have different physical meanings and implications. A perfectly flat surface can be under severe stress. In this case, an OSP-300 or any other technique using light interference, including CGS interferometry, cannot provide reliable information on stress. This is because the light reflection or interference is macroscopic interactions between light and the wafer surface region. Since inelastic light scattering is the nanometer scale interaction between light (photons) and wafer surface region (Si lattices near the surface), Raman spectroscopy, however, can provide micro or nanometer scale lattice strain/stress regardless of surface flatness. For understanding material properties in both macro and micro scale correctly, the combination of the two characterization methods should be used.

IV. SUMMARY

The importance of understanding macro- and micro-scale wafer shape changes during device fabrication process steps is emphasized. Two new, non-destructive in-line process monitoring systems, Optical Surface Profilometry (OSP-300) and Multi-Wavelength Raman Spectroscopy (MRS-300) systems were introduced as process induced surface profile and lattice strain characterization tools.

TiN/NiPt/$Si_{1-x}Ge_x$/Si (100) and $Si_{1-x}Ge_x$/Si (100) wafers are characterized using the newly developed very high magnification OSP-300 system after annealing with lamp-based RTP or and LSA systems. Global and local changes of wafer surface profiles were characterized and compared between the lamp-based RTP anneal and LSA. Changes in Ge content and lattice level stress in $Si_{1-x}Ge_x$/Si (100) wafers annealed under various LSA temperatures and dwell times were measured using a Raman spectroscopy (MRS-300) system. Significant changes in lattice strain/stress and possible Ge segregation after high temperature LSA were found.

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