Non-Contact, Image-Based Photoluminescence Metrology for Ion Implantation and Annealing Process Inspection

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Abstract. In this paper, we report results from a systematic evaluation of sensitivity, resolution and intrinsic capability of an RTPL system across a range of different implant conditions, including doses from 10^{11} to 10^{16} cm^{-2} and energy from sub-keV to the MeV level. Comparisons are made to existing non-contact and physical methods across this broad range of implant conditions. The RTPL system is shown to correlate well with all techniques investigated while offering sensitivity improvements for resolving critical parameters, such as energy, which is a reflection of the depth of the as-implanted junction. In addition, rapid, high resolution, full-wafer map imaging and smaller micron-scale scans enable visual characterization of uniformity under both as-implanted and annealed conditions. Visual inspection capability is shown to be especially useful for characterizing annealing processes and revealing unique residual defect patterns.

Keywords: ultra shallow junction, photoluminescence, metrology, as-implanted.

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INTRODUCTION

Current generation source-drain extension implants employ relatively low energy and high implant dose to create junctions on the order of 10 nm below the substrate surface. The integrity of these so called, ultra-shallow junctions (USJ) is critical for optimum device performance where short channel effects and leakage will prevail in improperly formed devices. Typically, these junctions are characterized using electrical methods (Sheet Resistance, (Rs)) and/or physical methods (SIMS, TEM). Although effective within specific parameter windows, such methods require either electrical activation of the p-n junction – which requires a subsequent anneal – or they employ a destructive technique. Other less stringent implant steps, such as threshold voltage adjustment and channel engineering implants require similar characterization in order to develop and monitor their integrity. A nondestructive, in-line process inspection approach on monitor and patterned wafers is especially desired to reduce cost and latency associated with existing physical measurements. A specialized, non-contact, carrier lifetime-based room temperature photoluminescence (RTPL) method meets this demand. The RTPL system, which uses a novel excitation path design to achieve carrier confinement, device-suitable probing depth and submicron scanning resolution, offers a quick, non-destructive reading which is sensitive to dose, energy, leakage and the amorphous depth of the implanted layer while providing a full-wafer map image of the as-implanted and after anneal uniformity.

PHOTOLUMINESCENCE METROLOGY

Low and room temperature spectroscopic PL systems have been used for many years and are well established for defectivity characterization in silicon materials.(1, 2) However, such solutions are impractical for high volume, in-line process control. In contrast, the edge-band, carrier-lifetime-reliant RTPL system is well suited for nondestructive, high throughput damage and contamination assessment. The tool can operate in full wafer and micro mapping modes of operation. Simultaneously with the PL maps, surface reflectivity (SR) maps are collected. The RTPL measurement setup principles are illustrated in Fig. 1. The tool is equipped with two different wavelength lasers, called the Channel and the Bulk Probe. Depending on the desired probing volume (implantation energy), the Channel and Bulk Probes can be appropriately selected for evaluation. In the lateral dimension, laser beams are focused to a two micrometer spot by a system of lenses.

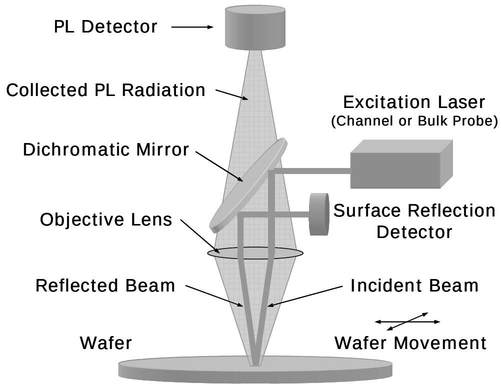

FIGURE 1. RTPL measurement setup.

Electrically active defects that are present in the bulk, such as post-implantation damage, lattice disturbances (crystal amorphization) or metal contamination are likely to be detected only in the PL image. Surface defects such as particles, growing faults or etching pits are predominantly seen in SR images. Surface defects may also be identified in PL images, if they modify the light reflection/ absorption path.

Differential and average PL signals along with their standard deviations provide useful and relevant information for quantification, inspection and control of ion implantation and annealing processes. To this goal, process limits can be defined using PL and surface reflectivity responses. In addition, results can be compared against a tabulated or otherwise pre-determined data repository (obtained via correlation) in order to quantify process excursions in terms of dose, energy or annealing condition variation.

RESULTS

A range of different implant conditions, including doses from 10^{11} to 10^{16} cm^{-2} and energy from 60 keV to 900 keV for ^{31}P species, as well as high ^{11}B doses implanted at 500 eV typical for USJ applications have been analyzed with the RTPL technique. An impact of different annealing conditions from relatively long, low temperature solid phase epitaxial (SPE) regrowth to very short, high temperature flash and laser anneals on damage removal is presented. Signatures of typical USJ annealing methods are illustrated using PL inspection (PLi). The level of damage is quantified in PLi arbitrary units.

As Implanted Samples

Figures 2 and 3 summarize the relationship between implantation dose and energy on PLi, respectively, for ^{31}P specie. Depending on the implantation conditions, the Channel and Bulk Probes were used for data collection.

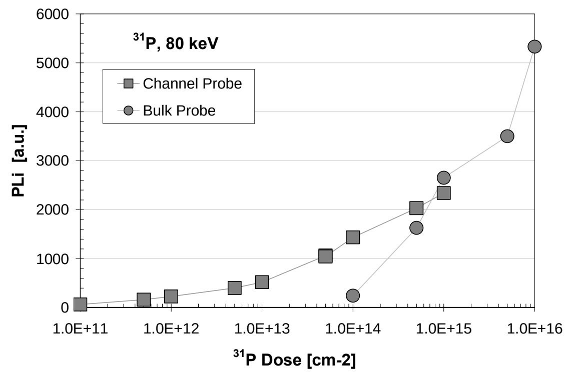

FIGURE 2. Impact of implantation dose on PLi levels for ^{31}P specie implanted at 80 keV.

Dose and energy sensitivity and detectability data are shown in Table 1. The data indicate that at applied implantation conditions, changes in dose and energy in the sub-1% range can be detected by PLi. Similar performance can be achieved for typical low energy, high dose USJ implantation conditions. High sensitivity and good measurement precision of the RTPL instrument enable imaging of damage uniformity over the entire wafer area; see Fig. 4, where implanter-specific variations in damage level over the entire wafer area are revealed. At a given equivalent implantation dose, despite differences in the implantation specie, the PLi signals can be effectively correlated to physical dimensions of the damaged layer, see Fig. 5 where PLi levels versus amorphous layer thickness, determined by TEM, are shown.

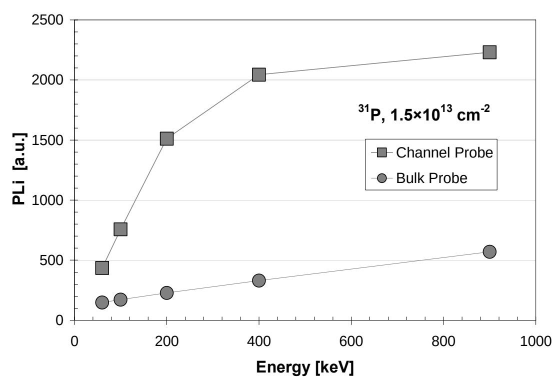

FIGURE 3. Impact of implantation energy on PLi levels for ^{31}P specie implanted at a 1.5×10^{13} cm^{-2} dose.

TABLE 1. Dose and energy sensitivity and detectability for ^{31}P specie implanted at constant energy (80 keV) or dose (10^{13} cm^{-2}), evaluated with (a) Channel or (b) Bulk Probe, using $D = 3\sigma / S$, $\sigma = 0.1\%$.

	Dose [cm^{-2}]		**Energy [keV]**	
	~$10^{13(a)}$	~$10^{15(b)}$	~$100^{(a)}$	~$500^{(b)}$
Sensitivity, *S*	0.39	0.42	1.10	0.67
Detectability, *D* [%]	0.76	0.71	0.27	0.45

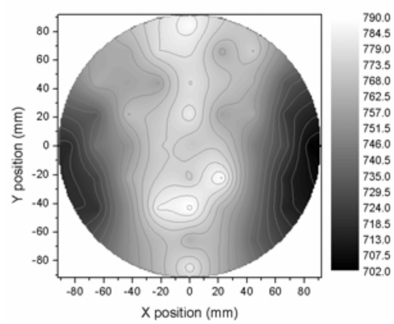

FIGURE 4. Ion implanter signature, ^{31}P, E = 60 keV, $C_s = 1.5\times10^{13}$ cm^{-3}, as-implanted sample.

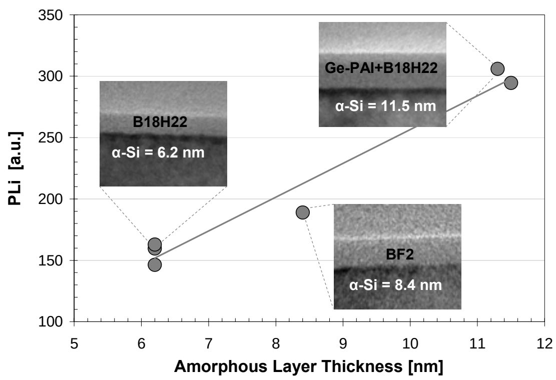

FIGURE 5. Correlation of PLi levels to amorphous layer thickness for USJ samples implanted at 10^{15} cm^{-2} equivalent dose. The thickness values were determined by TEM.

Annealed Samples

Selection of annealing conditions necessary for doping activation and damage removal at limited diffusion and relative insensitivity to pattern effects is absolutely critical for integrity of USJ formation. Suitable, high throughput and preferably non-destructive metrology is an important component of the effort. The RTPL inspection technique, with its quantifiable output, macro and micro mapping, sub-micron scanning resolution and high sensitivity to residual defects offers new possibilities in addressing these challenges.

Figure 6 shows full wafer and micro PL imaging of an ion-implanted wafer after short annealing, likely with a stripe-shaped laser beam, where stripping caused by beam overlapping can be clearly identified. Double- pass annealing reduces the residual damage in the region, as evidenced by PLi reduction from about 10.5 to 9.8 a.u. Based on the overall wafer average PLi level, it seems that the damage is not completely removed in the sample, as PLi values about 5 a.u. or lower are more typical for damage-free wafers.

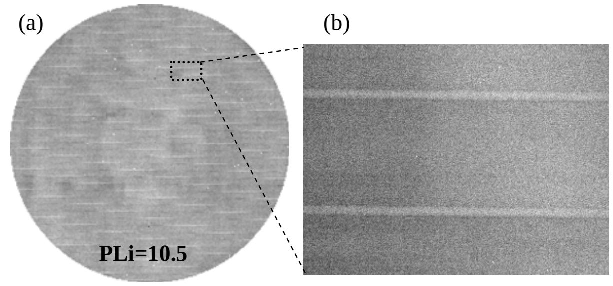

FIGURE 6. (a) PL full wafer map and (b) micromap showing close-up of stripping caused by overlap region.

The impact of typical annealing methods (SPE, spike, flash or laser) on damage removal and wafer-level uniformity is illustrated in Fig. 7 for a set of ^{11}B, 1×10^{15} cm^{-2}, 500 eV implanted samples. No preamorphization implantation was applied in this case. A large disparity in PLi levels within 5 to 110 a.u. range is observed. Note that significant uniformity problems are revealed for the annealing scenarios. For example, SPE clearly leaves behind considerable damage with PLi=110 a.u., while the spike, flash and laser anneal methods pose wafer uniformity challenges. Flash annealing led to the overall lowest (best) PLi levels of around 5 a.u., while laser annealing was not only less effective in removal of the damage, but also exhibited serious uniformity (stitching) problems.

Unique, sub-micron scale scanning resolution of RTPL enables complementary insights on damage removal capability of the annealing techniques. Figure 8 shows a series of 200 µm × 200 µm PL images, taken with 1 µm step resolution for a set of

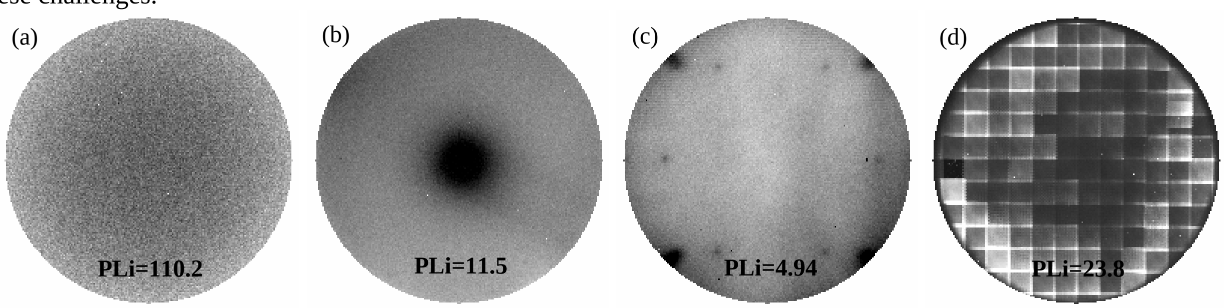

FIGURE 7. PL images of post-implantation annealed samples illustrating signatures of annealing equipment; (a) SPE, (b) spike, (c) flash, and (d) laser. All samples implanted with ^{11}B, 1×10^{15} cm^{-2}, 500 eV (without PAI).

^{11}B, 1×10^{15} cm^{-2}, 500 eV implanted samples. In this case, a germanium preamorphization step was used prior to boron implantation

The samples were subsequently subject to a variety of anneals including SPE, spike and flash. Consistently, the SPE anneal is characterized with incomplete damage removal as indicated by high PLi values. Due to the very high defect densities and small defect size, the individual defects cannot be resolved in these samples. The spike and Flash I processes led to better damage removal as compared to SPE, with PLi levels of around 12 a.u. and 29 a.u., respectively. The residual defect sizes in both cases remain too small to be individually resolved. In contrast, the more aggressive Flash II and III anneals lead to formation of large extended defects which can be easily imaged by PL. Note that the Flash II anneal produces low PLi levels on average, as the defect density is relatively small. Flash III annealing leads to a massive formation of slip defects, which are not necessarily directly attributed to the implantation process, yet result in high PLi levels indicative of residual damage. This residual, post-annealing damage deteriorates device performance due to excessive junction leakage. The damage, as assessed with PLi, is well correlated to junction leakage current, see Fig. 9.

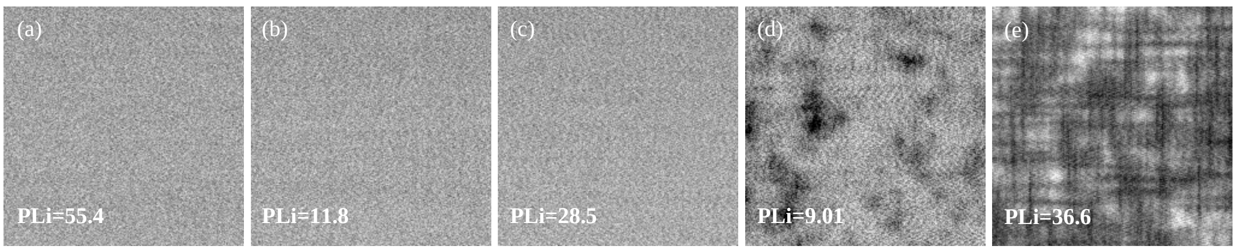

FIGURE 8. PL micro-images of annealed samples illustrating residual defectivity signatures of annealing process; (a) SPE, (b) spike, (c) flash I, (d) flash II, and (e) flash III; ^{11}B, 1×10^{15} cm^{-2}, 500 eV, with PAI implantation; 200 µm × 200 µm, 1 µm step images.

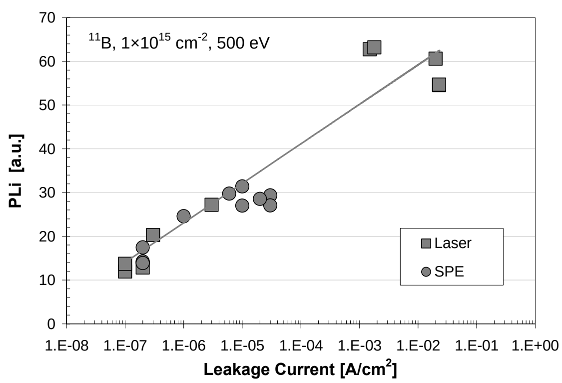

FIGURE 9. Correlation of junction leakage by RsL method (4) to residual defectivity by PLi.

SUMMARY

In this paper, a well-characterized, non-destructive, non-contact system utilizing room temperature photoluminescence (RTPL) is shown to offer significant benefits for the measurement of implant dose and energy as well as the characterization of thermal anneal processes. The following attributes are characteristic of the PL metrology system in this study:

- Ability to measure minute changes in implant conditions, enabling detection of sub-1% variations in both dose and energy
- Precise determination of residual damage following thermal annealing, such as SPE, spike, flash and laser anneals
- Detection of macro-uniformity effects using full wafer scanning, enabling troubleshooting and process optimization on a global level
- Determination of the local microstructure by using micro-scans for the detection of lattice-based defects in milli-second anneal processes

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