Ultra-shallow Junction Metrology Using the Therma-Probe Tool

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Abstract. Therma-Probe tool has long been established to monitor the implant dose. In this work, we demonstrate that the unmodified tool is also capable of meeting the stringent demands of junction depth monitoring for the current and future technology nodes. The ultra-shallow junction (USJ) application development was carried out on the Therma-Probe tool using the wafers provided by the International SEMATECH.

The measured Therma-Wave signal varies as a sinusoidal function of the SIMS-based junction depth (at 1E18 ions/cm\textsuperscript{3}) for wafers with various dose and energy conditions annealed around 1000\degreeC. A theoretical model has been proposed to explain the source of the experimental signal response to the junction depth. A correlation table may be set up using the junction depth values provided by a reference method such as SIMS (Secondary Ion Mass Spectrometry) or SRP (Spreading Resistance Profiling); or the sheet resistance obtained using a 4-point probe system. The existing user interface software has been modified to allow reporting the results directly terms of the correlated junction depth.

For production-worthy throughput conditions, the short-term precision is found to be <0.5\AA, while the long-term stability is shown to be <2 \AA for a variety of wafers tested. The USJ application package for the Therma-Probe tool offers a method to monitor wafers using an in-line, fast, and non-destructive metrology in production.

Key Words: USJ, non-destructive metrology, RTP, 300mm.

INTRODUCTION

This paper presents the results of a gauge study performed to qualify the new application to measure the ultra-shallow junction (USJ) depth using the Therma-Probe tool [1]. The Therma-Probe has been widely used for implant dose monitoring since its introduction in 1984. The current and future demands of the ultra-large scale integration (ULSI) device manufacturing further necessitate a tight control of the depth of the junctions, especially the source and drain extensions, after the annealing step [3]. It was found in early experiments on the Therma-Probe system that the unmodified tool is also capable of monitoring the junction depth (X\textsubscript{j}) after annealing [4]. A systematic investigation followed that resulted in the added application of the Therma-Probe, the USJ application. International SEMATECH provided the wafers used in this study under a joint-development agreement. The results include the Therma-Wave (TW) signal variation with junction depth and sheet resistance, the short-term repeatability (precision), as well as the long-term (15-day) stability.

The measurement of USJ depth poses a challenge to the metrology equipment suppliers. A significant driver is the move to 300mm production. Techniques like Secondary Ion Mass Spectrometry (SIMS) or Spreading Resistance Profiling (SRP) cannot probe product wafers and thus require the expense of monitor wafers, in addition to being time-consuming. By comparison, the Therma-Probe may directly measure a small test area (40-100 \mu\textsuperscript{2}) found on product wafer scribe lines; or generate a 137-site contour map on a blank monitor wafer.
EXPERIMENTAL SET-UP

The thermal-wave technology underlying the Therma-Probe system involves measuring the change of optical properties when a material is excited by an intensity-modulated light source (the pump laser) [5]. The absorption of the incident energy causes the sample's complex index of refraction to vary at the frequency of the modulation source. The variation in index of refraction is detected by monitoring the modulated reflectance of an optical laser (the probe laser) from the sample surface (Figure 1). The measured TW signal reports this AC quantity during the measurement [6].

FIGURE 1. Photo-modulated reflectance (PMR) schematic diagram for the Therma-Probe.

For an annealed sample, the gradient of refractive index in the junction layer extends to a depth where the carrier concentration approaches that of the bulk, around $1 \times 10^{18} \text{ions/cm}^3$. The depth of this layer is the junction depth, which also determines the intensity and phase of the reflected probe signal. The reflected probe intensity exhibits a sinusoidal profile with depth similar to a thin film interference effect, except that the reflecting surface is not a sharp boundary but rather an integral effect resulting from a gradient of the refractive index.

SAMPLES AND MEASUREMENTS

The 200mm wafers were prepared using a variety of implant and annealing conditions with boron and arsenic dopants. B-doped wafers were implanted at $5 \times 10^{14}$ and $3 \times 10^{15} \text{ions/cm}^2$ with energies varying from 0.4 to 6 keV, followed by annealing at 990C for 5s. Another B-doped set consisted of wafers with $1 \times 10^{15} \text{ions/cm}^2$ dose at similar energies with 1000C, 10s annealing. The As-doped wafers consisted of 2-50 keV implant at dose ranging from $5 \times 10^{14}$ to $3 \times 10^{15} \text{ions/cm}^2$, and annealed at 1000C for 10s. Identically processed lots of wafers enabled parallel measurements on the Therma-Probe, along with SIMS and other destructive analysis to enable TW system qualification and signal correlation.

The measurements made on the Therma-Probe tool comprised 137-site area contour maps with 3mm edge exclusion, unless noted otherwise. The repeatability runs were performed using a 5-site custom template mode. Due to the partially annealed nature of the USJ wafers the measurement positions were slightly varied within a small area around the nominal sites so as to minimize the contribution of in-situ effects to the tool performance evaluation.

RESULTS AND DISCUSSION

Results from both B and As-doped wafers are shown in the following sub-sections and correlated to SIMS and sheet resistance data. A theoretical model is also fitted to experimental data. Additionally the short- and long-term performance is illustrated.

A. Trend With Sheet Resistance And SIMS Junction Depth

Figure 2 displays the results for the Therma-Probe measurements on the B-doped wafers. The SIMS Xj and the sheet resistance are simultaneously plotted as a function of the TW signal.

FIGURE 2. SIMS Xj and Rs trend with the TW signal.

Notice that the junction depth and the sheet resistance (Rs) anti-correlate with the signal, except
for one wafer (data points surrounded by the oval). This behavior provides a strong indication of the signal to correctly predict variation of the process in a manufacturing environment. The deviation from the overall behavior for one wafer could be due to various causes. The measurement area of the 4-point probe is about a factor of $10^3$-$10^4$ times the probe area of the Therma-Probe 1µm beam spot. For example, due to this very different spatial scale there could be a local change observable by the Therma-Probe method, yet not captured by the 4-point probe.

**B. TW Signal Response to $X_j$**

The TW signal also offers a convenient correlation to the measured SIMS $X_j$ values directly. For this purpose we present the TW signal measurements on the As-doped wafers vs. the junction depth at $1 \times 10^{18}$ ions/cm$^3$ dopant concentration.

![Figure 3: TW signal variation for As-doped wafers at increasing dose values when the junction depth variation was attained by ion energy scaling for the same annealing condition.](image)

The above figure shows that the various dose values follow a periodic function. Within each quarter of the curve the signal varies linearly with the $X_j$, enabling a simple correlation. The sharp rise/fall of the plot in the linear regime supports a high sensitivity of the TW signal to the junction depth variation. Near or at the peaks and valleys of the curve the sensitivity is reduced.

The periodic shape of the curve is fitted with a theoretical model developed by Opsal [4] in figure 4. The normalized signal data points from figure 3 are fitted to the theoretical model. The interference effect arises from the gradient of the refractive index forming the junction region reflected by the probe laser beam. Therefore, the shorter the probe laser wavelength, the shorter the period of the response function, and higher the signal sensitivity to the junction depth. Of course, the period and the absolute amplitude of the response will also depend on the optical properties of the junction layer.

![Figure 4: Normalized TW signal based on theoretical model (solid line) as a function of the junction depth fitted to the normalized experimental data from figure 3.](image)

**C. Short-term Repeatability (Precision)**

Table 1 displays the typical results of a 30-cycle precision run without load and unload (LUL). Spatial averaging over a 20x20µm$^2$ area was performed in a 4-site scheme; and site-overlap during successive cycles was avoided by micro-stepping after each cycle. The first column gives the wafer processing parameters, followed by the columns with results for the TW signal and the correlated $X_j$ values. The junction depth values are based on the extrapolation of the piece-wise linear fit between the TW signal and SIMS $X_j$.

![Table 1. 30-cycle precision results.](image)
The above table shows that the 30-cycle precision is <0.5Å for the wafers in this study.

D. Long-term Stability

A 15-day stability run was conducted on selected wafers at 5-sites using the same measurement scheme as for the short-term precision runs. Table 2 exhibits the 15-day standard deviation by site for the correlated junction depth values from a fit between the TW signal and the SIMS Xj provided.

<table>
<thead>
<tr>
<th>Wafer Parameters</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tr>
<td>1E15 As, 4 keV</td>
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<td>5E14 As, 2 keV</td>
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<td>1.9</td>
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<td>1000°C, 10s</td>
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The above table exhibits the 15-day stability to be under 2Å on the average. The Therma-Probe capability to monitor production thus appears to be excellent and well within the typical junction depth window of ±5 Å.

CONCLUSION

The capability of the present Therma-Probe system for the USJ application has been demonstrated in this study. Additional user interface screens enable the user to measure and generate maps, reports etc. in terms of the correlated junction depth. The TW signal is shown to trend with both the sheet resistance and the SIMS junction depth values with a high sensitivity. The long-term stability is found to be under 2Å. The spatial resolution combined with the exhibited performance enable the tool to do in-line production monitoring.

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REFERENCES

1. The metrology tool Therma-Probe, a registered trademark of Therma-Wave Inc., Fremont, CA 94539, USA.


