Photomodulated Reflectance Measurement Technique for Implantation Tilt Angle Monitoring

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***Abstract*—Photo-modulated Reflectivity Measurement (PMR) is an excellent technology for implantation dose and tilt monitoring of as-implanted pre-annealed production wafers. SEMILAB PMR-3000 is an in-line monitoring unit for ion implantation monitoring use prior to the thermal annealing process step. The enhanced optical system ensures the measurement on the whole dose range without insensitive regions in the mid-dose range. Typical dose detectability is <0.5% (1sigma). The resolution of tilt angle detection is <0.1° (1sigma). This sensitivity to tilt angle fulfills the requirements of state of the art process control requirements.**

Keywords—ion implantation, dose, tilt angle, photomodulated reflectivity

I. INTRODUCTION

One of the main challenges facing the fabrication of CMOS devices is the requirement for increasingly tight control of implantation parameters such as dose and tilt angle of special implants, e.g. lightly doped drain, halo, super-steep retrograde channel, large tilt angle punch through stopping implants, etc. This has created a need for improved metrology to develop and control doping processes with rapid turnaround and with the capability for in-line uniformity mapping.

Until the 0.25 µm process node ion beam incident angle was not considered as a critical factor in process control as the technology was real planar technology [1]. However, as device size shrink they become increasingly sensitive to variations of ion beam angular properties [2] as modern CMOS technology is no longer planar literally, since many of the vertical dimensions could not be scaled in the same pace as the lateral ones resulting in high aspect ratio features on the wafers.

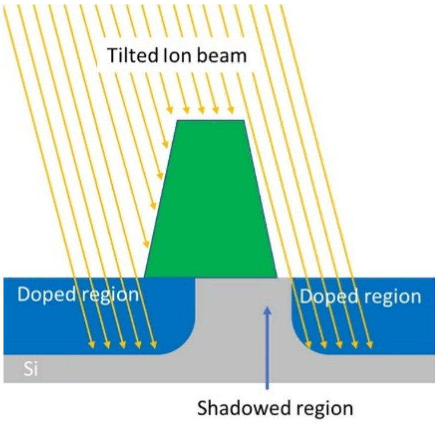

Fig. 1. Shadowing effect during ion implantation

Introduction of real 3D structures such as finFET and 3DNAND technology put further challenges on implantation tilt angle specifications [3]. The resist height and fin height to spacing ratio defines the maximum available implant angle where dopants can reach the foot of each fin. Failure to do so leads to loss in drive current [4]. Asymmetry in ion beam incident angle leads to device asymmetry [5] due to shadowing effects at the pattern edges of photoresist mask, gate or fin structures (Figure 1.).

To avoid shadowing effects many of the implants moved to zero tilt conditions from the conventional randomized, non-channelling 7° implant angle [1]. Ion channelling at 0° implant angle is unavoidable to <100> silicon wafers. This makes the dopant profile much deeper with a larger lateral straggle compared to random ions. <001> axial channelling is extremely sensitive to small variation in incident angle which makes ion angle control even more important.

It was shown that for high current implanters less than 0.5°, while for medium current implanters 0.1° of angle control is required to ensure uniform doping for zero tilt well implants and to suppress the device parametric variation at high angle halo implants [2]. These requirements are relaxed when quad mode implants are applied with 90° wafer rotation. For sub-65 nm source-drain extension (SDE) implants beam steering must be controlled to <0.25° for single step SDE and 1° for quad mode SDE steps.

Keeping ion beam angle in precise control in production or after maintenance is a key and requires high quality tool monitoring metrology [6]. In our paper we present the excellent tilt angle measurement capabilities of the PMR-3000S in-line implantation monitoring tool.

II. EXPERIMENTAL

A. *Photo-modulated optical reflectivity*

Photo-modulated Optical Reflectivity measurement (PMR) based on the phenomenon of Carrier Illumination™ is a non-contact, non-destructive technology for implantation monitoring on as-implanted pre-annealed production wafers with a measurement spot size smaller than 3 µm.

The working principle of the measurement is based on the known phenomenon that optical excitation of a sample (surface) results in the change of its reflectance. In the case of semiconductor samples, the mechanisms responsible for the reflectance change include the creation of excess carriers and heat gradient due to the excitation. The PMR measurement process focuses mainly to the former thus the optical excitation is provided by an intensity modulated generation laser of 808 nm ("RED" laser). The intensity modulation is strictly sinusoidal with frequency of 2 kHz that results in a quasi-static process leading to high signal-to-noise ratio. The generation (RED) laser creates excess carrier (and heat) gradient that forms an index of refraction gradient. The change of the index of refraction is detected by the probe laser of 980 nm (IR laser) through the change in the sample reflectance. The incident intensity of the probe (IR) laser is kept constant, while its reflected intensity is monitored. A sinusoidal change in the reflected probe (IR) laser intensity can be observed by means of the Lock-In technique as the effect of the intensity modulated excitation. This principle is depicted in Fig. 2 and Fig. 3, one can recognize that the light of the two lasers is focussed to the sample together into a spot size of ~3 µm. Therefore, the PMR measurement can be carried out with high spatial resolution that enables the creation of wafer maps and - via the pattern recognition system - the high-precision measurement of the patterned samples.

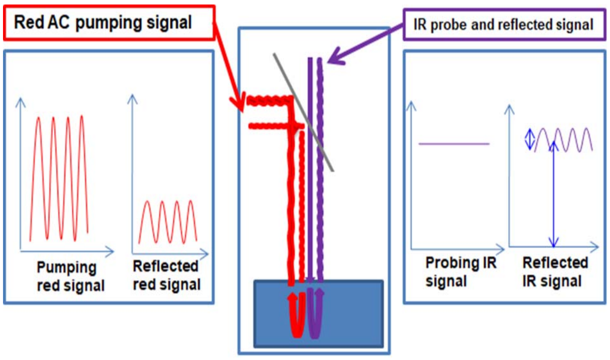

Fig. 2. Illustration of the generation (RED) and probe (IR) laser signal shapes applied in the PMR measurement

The raw PMR signal itself is defined as the relative change of the reflected probe (IR) laser intensity (i.e. $\Delta R/R$). The signal is composed by dividing the reflected AC and DC IR laser components both measured by the Lock-In amplifier that is set to the modulation frequency of the RED laser (2 kHz). The PMR signal depends on both the implant damage and carrier concentration-change. This results in high sensitivity to the implant dose and energy and - as it is shown in this paper - even to the implanting tilt angle. This means that the PMR signal is a (monotonous) function of several parameters. Thus, the PMR tool has to be calibrated by a series of samples for which one particular physical parameter (e.g. the implant dose) is stepped while the other parameters are kept constant. In other words, the PMR technique can measure changes in a selected implantation parameter for otherwise constant conditions, and a known reference sample set of those conditions is needed for calibration.

According to the former it is clear that the PMR measurement should be carried out after the ion implantation but prior to any annealing process step. Since annealing reduces or even abolishes the implant damage the sensitivity of the PMR measurement significantly decreases if performed after the annealing of the sample. Accordingly, all the data presented here were taken by applying as-implanted, non-annealed samples.

It is to be mentioned that the Lock-In technique measures the amplitude of the reflected AC IR component together with its phase relative to that of the modulation on the RED laser. This phase depends on many sample parameters as well, and how to extract information is the focus of continuous development. Currently, this phase means that the raw PMR signal value can be negative in the corresponding phase ranges.

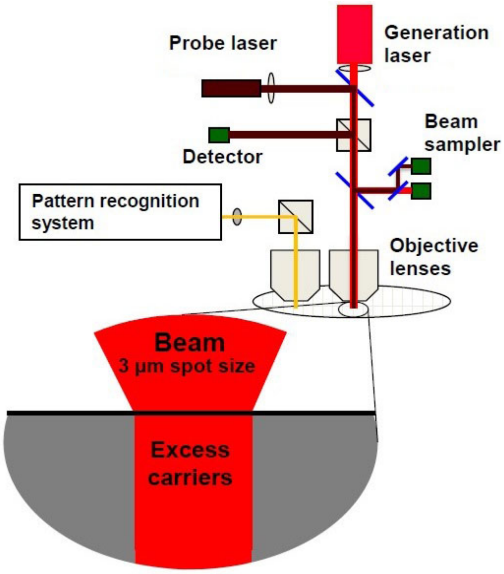

Fig. 3. Schematic outline of the optical setup of the PMR measurement

Fig. 4. A photo of Semilab's PMR-3000 tool

B. PMR-3000 tool

The SEMILAB PMR-3000 shown in Fig. 4. is an ion implantation dose monitoring unit for in-line ion implantation monitoring use preceding the thermal annealing process steps. The PMR tool is sensitive in a wide range of implant dose level ($5x10^{10}$: $5.5x10^{16}$ ions/cm^2).

The use of a built-in laser light intensity stabilization system results in an enhanced PMR signal repeatability of $3\sigma<0.15\%$ and stability of $3\sigma<0.45\%$. The PMR signal, being a nonlinear function of the physical parameters, shows varying sensitivity at different ranges of those parameters. Thus, a reference sample is required to characterize the performance of the tool. The above values are valid for bare silicon wafers with thermally grown oxide layer of min. 100 nm thickness as reference samples.

Under the foregoing, the sensitivity should be given for every measurement parameter type (e.g. separately for the dose/tilt/energy etc. measurements). This is done by repeating the same measurement many times and calculating a standard deviation (σ) for the data averaged for every measurement point for each sample. The σ values given hereinafter were obtained by this process. Accordingly, this method gives σ values originating both from our tool and from the wafer inhomogeneities as well.

Both the generation and the probe lasers are in the near-infrared regime making the metrology not only non-contact but even non-destructive.

In addition, the PMR tool provides a measurement value corrected to most of the changing environmental parameters, e.g. the humidity- and temperature fluctuations, furthermore, there is a real-time focus-correction mechanism. Moreover, the PMR signal is signed and amplified to best fit the digital data processing. This end-value PMR signal is referred simply as PMR value in the foregoing.

The PMR-3000 is available with a pattern recognition option which enables the PMR measurements to be carried out on 50 µm x 50 µm testpads designated for this process step as laser spot size is less than 3 microns and stage accuracy is better than 5 microns.

C. Samples

For tilt angle measurements, 200 mm p-type single side polished (100) Si wafers were implanted with B at IBS France. As ion channelling occurs when the implant angle is set to 0°, the resulting dopant profile is very sensitive to small implantation angle variation. Samples were implanted with a ±2° angle variation around zero tilt. Negative degree implant angles were achieved by wafer rotation of 180°. Implant conditions were the following:

(i) starting position: 0° twist was when notch is at 12 o'clock
(ii) tilt direction: 6 o'clock edge away from the beam
(iii) twist: wafer turned clockwise

Low energy B implants for dose measurements were made at Innovion Corp, USA. All the implantation conditions are summarized in TABLE I.

TABLE I. IMPLANTATION CONDITIONS OF THE USED SAMPLES

Tilt angle measurements

Energy	Dose [ions/cm^2]	Twist	Tilt				
50 keV	5×10^{13}	112	-2°	-1°	0°	1°	2°

Dose measurements

Energy	Tilt	Twist	Dose [ions/cm^2]
3 keV	6.4°	2.7°	$5x10^{12}$; $4.5x10^{13}$; $5x10^{13}$; $5.5x10^{13}$; $4.5x10^{14}$; $5x10^{14}$; $5.5x10^{14}$; $4.5x10^{15}$; $5x10^{15}$; $5.5x10^{15}$

III. RESULTS AND DISCUSSION

First, the dose sensitivity of the PMR tool was demonstrated by measuring the PMR value as the function of the implant dose in a wide range from $5x10^{12}$ to $5.5x10^{15}$ ions/cm^2. In this series of measurements, the samples were implanted with Boron ions of 3 keV, while the tilt and twist angles were 6.4° and 2.7°, respectively. The dose ladder can be seen in TABLE I, and the results are depicted in Fig. 5.

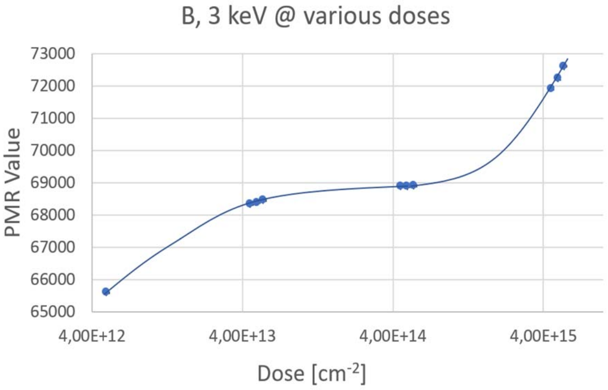

Fig. 5. The PMR value as a function of the implant dose

It is to be mentioned that the result points were obtained by averaging the data from 9 sites in the case of each wafer and even the ±3σ error bars are so small they are hard to recognize. The line connecting the presented result points has no physical meaning, it is not a fit rather a guide to the eye. The DC power of the generation laser was set to 40 mW, while that of the probe laser was 20 mW in these experiments. As it can be deducted from Fig. 5, the PMR value is fairly sensitive at the low (~10^{10} : 10^{12} ions/cm^2) and high (10^{15} : ~$5x10^{16}$ ions/cm^2) dose range. Moreover, the optical system of the PMR-3000 tool ensures the measurement of the whole dose range without insensitive regions (i.e. regions of 0 slope) in the mid-dose range. Typical dose detectability is 0.5% (1σ) and the maximum value is <8%.

The ion implant tilt angle sensitivity of the PMR tool was investigated in the subsequent measurement. Samples were implanted by 50 keV B ions of $5x10^{13}$ ions/cm^2 dose. The twist was 112° in both cases and the tilt was varied from -2° to 2° as it is seen in Table 1. The results are plotted in Fig. 6. Here an averaging over 24 sites was carried out in the case of each wafer, and error bars indicate the ±1σ deviation. The “normalized PMR value” term on the y axis means that each PMR value was divided by that obtained at 0° tilt angle. The DC power of the probe laser was 20 mW, and that of the generation laser was 40 mW again.

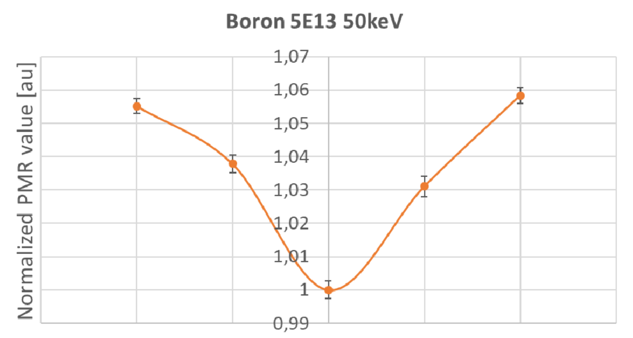

Fig. 6. The normalized PMR value as a function of the implanting tilt angle

As the precision of the starting wafer orientation is ±0.5° with respect to the <001> plane and minus degree tilts are obtained by 180° rotation, asymmetry of the tilt-curves is not surprising. The implant angle precision is guaranteed with ±0.5° by our vendor, which can cause another shift in the nominal x-axis values. The resolution of tilt angle detection is 1σ~0.1°.

PMR is capable to detect tilt angle variation in case of low dose implantation of light B ions with 0.1° (1 sigma) resolution. The Carrier Illumination™ response is related to the vacancies produced during non-amorphizing ion implants based on Vandervorst et al. [7]. This sensitivity to tilt angle fulfills the requirements of state of the art process control.

IV. CONCLUSION

The PMR-3000 ion implant monitoring metrology of Semilab Semiconductor Physics Laboratory has enhanced sensitivity in a wide range of implantation regimes:

The most significant improvement has been achieved in the implant dose sensitivity in the medium-dose implantation regime (5×10^{13} : 5×10^{14} ions/cm^2). The results suggest that the most serious drawback of the preceding PMR measurement technique, namely the existence of insensitive regions (i.e. regions of 0 slope) is eliminated.

The new metrology also has an excellent sensitivity to the variation of the implantation tilt angle enabling its control with a resolution of ~0.1°. This accuracy meets the requirements of the most sensitive implantation technologies. Enhancement of the optical system contribute to advanced dose detection sensitivity and stability of the PMR-3000 tool.

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