Dopant Activation and Profile Determination with an Elastic Material Probe (EM-Probe)

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Abstract. In this paper, a new method is described for determining the near surface electrically active dopant density (N_{SURF}). This is a powerful new method that allows for the monitoring of Activation for USJ Structures. The technique uses a non-penetrating, non-damaging probe that elastically deforms to form a contact on the bare or native oxide covered surfaces of USJ structures. Advanced Capacitance-Voltage (CV) methods are used to determine the electrically active dopant, not carrier, density. The technique and physics will be described in detail along with several case studies.

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INTRODUCTION

The performance of MOS transistors depends highly upon the design of Ultra-shallow junctions associated with the Source-Drain extensions (SDE). The single most important aspect associated with the implanted S/D structure is dopant activation.

Generally, four point probe (4pp) methods have been used to measure the sheet resistance (R_S) of the USJ layers. Many types of Four Point Probes have been developed that reduce penetration into the USJ layer by conditioning or non-contact. It is important to remember that the R_S value depends on the integrated charge of the S/D structure and, the majority carrier mobility (μ_p or μ_n). Recently, the use of R_S alone has been questioned as an accurate way to monitor dopant activation. For one, there is a junction depth dependence and also, a mobility dependence (1). It is argued that it is unlikely that the S/D mobility is equivalent to that of bulk silicon due to additional processing, short anneal times and Preamorphization implants (PAI). It is therefore highly desirable to utilize a parameter that is sensitive to activation only and not x_J or carrier mobility.

A parameter suitable for dopant activation control has been developed and is the electrically active near surface dopant density (N_{SURF}). This paper describes a recently developed method to measure N_{SURF} with a single, non-penetrating, non-damaging Elastic Material-Probe (EM-Probe) (using similar equipment and technology as in reference 2). N_{SURF} is measured with a Capacitance-Voltage (CV) based method that uses the equilibrium rather than the non-equilibrium CV data. The N_{SURF} value represents the average active dopant density within the equilibrium space charge region. For USJ structures, this is about 10 to 30 Angstroms.

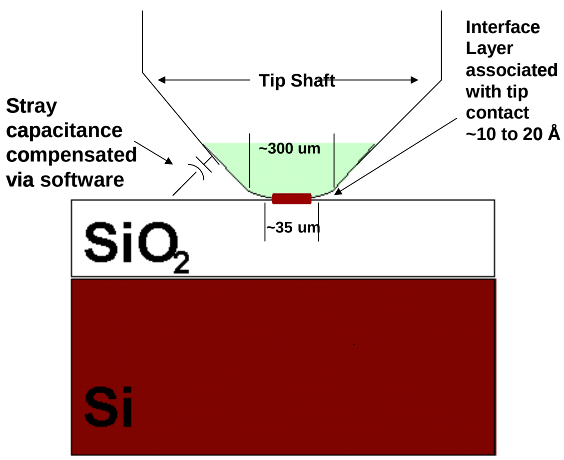
Another important parameter of interest is the junction quality. This will also be discussed in the paper and is also critical in the design of USJ SDE structures.

EM-PROBE DESCRIPTION

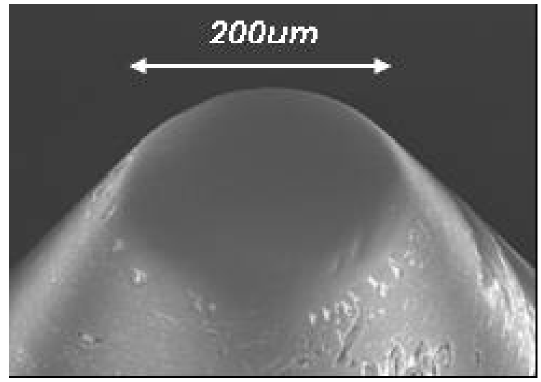
A basic description of an EM-probe Metal-Oxide Semiconductor Capacitor (MOSCAP) is given below. The EM-probe is used to contact an MOS or bare semiconductor surface by using a specially prepared probe (3). Generally, a metal is used, but any suitable elastic material can be used. There are two types of EM-probe probes available; one for Capacitance-Voltage (CV) applications and the other for Current-Voltage (IV) applications. These are generally referred to as Type A and Type C probes respectively. Type A probes have a native metallic oxide present on the probe surface. This oxide serves as a barrier to current flow and allows for CV measurements on thin dielectrics without the effects of leakage current. Type C probes are made of a metal whose properties are such that no oxide forms on the probe or the oxide that does form is conductive. These properties make the Type C probe suitable for IV applications. All EM-probes are mounted on a kinematic bearing system with controlled descent and ascent. The kinematic system ensures that no probe scrubbing occurs. This is essential. The probe has been used to measure 6 Angstrom MOS oxides with a multiple day precision of 0.1 Angstrom. The Gate dielectric area has been another application for the EM-probe.

The EM-probe contacts are formed by lowering the probe onto a semiconductor surface or dielectric and elastically deforming the probe material. The resultant contact diameter is typically 40 to 60 um and depends on the probe geometry and applied force.

An illustration of the EM-Probe Contact is shown in Figure 1.



a)



b)

FIGURE 1. a) Illustration of EM-Probe contact to form Gate of MOS Capacitor. b) an SEM Photograph of EM-Probe Tip and Surface.

EM-Probe CV Based Method For Determining N_{SURF}

CV based methods for measuring carrier and electrically active dopant density are well established and have been used for many decades (4,5). These methods either utilize the non-equilibrium or deep depletion CV data to calculate the carrier density profile or equilibrium CV data to calculate an average electrically active near surface dopant profile. An equilibrium CV curve is in steady state with the existence of a surface inversion layer for gate voltages equal to and greater than the threshold voltage of the MOS Capacitor (MOSCAP). Equilibrium and non-equilibrium EM-Probe CV curves are shown in Figure 2.

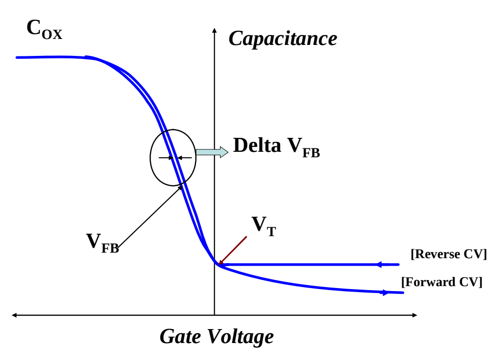


FIGURE 2. General CV curves depicting the non-equilibrium and equilibrium CV regions. The Forward sweep CV data represent non-equilibrium and the Reverse sweep CV data represent equilibrium CV data. Generally a light is used to generate carriers and form a surface inversion layer.

The CV data are acquired by sweeping or pulsing the gate voltage from Accumulation to Inversion (Forward CV) and then establishing equilibrium using a light source and sweeping or pulsing the voltage from Inversion to Accumulation (Reverse CV). A carrier density profile can be obtained from the forward or deep depletion CV data and an average N_{SURF} is obtained from the equilibrium CV curve. It is important to note that N_{SURF} is the average near surface electrically active dopant density and is not the carrier density.

There are limitations to the use of non-equilibrium CV data that limit the measure of carrier density to within the 10^{18} cm^{-3} range. For the case of N_{SURF}, values can typically be measured with equilibrium CV into the 10^{18} cm^{-3} range of dopant density. However, these are cases where the gate dielectric Capacitance Effective Thickness(CET) is anywhere from 50 to 1000 Angstroms. If the CET values are around 20 Angstroms, then measurements of N_{SURF} into the 1e20 cm^{-3} can be easily measured with good sensitivity.

Several physics considerations need to be made. First, at higher dopant levels, increased interaction between the high number of dopant atoms and the silicon density of states occurs leading to narrowing of the Energy Gap. This phenomenon has been well studied and applied for device performance prediction. A general equation for bandgap narrowing is,

$$\Delta E_G = (22.5\ \text{meV})(N/10^{18})^{1/2} \qquad (1)$$

It is difficult if not impossible to establish these measurements with conventional gate structures due to excessive gate leakage currents. An EM-Probe was used to form a MOSCAP on bare or native oxide covered USJ samples. The probe high-k dielectric discussed earlier serves to reduce the direct tunneling current.

In addition to monitoring Implant activation, it is sometimes desirable to obtain information about the actual dopant or carrier profile. For example if there is surface depletion or pile-up of dopants due to segregation effects, this can influence the value of N_{SURF} since the real profile may depart from a BOX type profile. In this paper, an incremental N_{SURF} and incremental R_S method have been made and compared to a USL SRP (Ultra-shallow Layer Spreading Resistance Profiling) result. The incremental R_S method contains the largest uncertainty since carrier mobility must be assumed in order to convert to a carrier density.

The incremental techniques are simple but tedious. First, EM-Probe CV and 4pp R_S measurements are made on the top surface. Then, the wafer is oxidized in Hydrogen Peroxide (H_2O_2) at 80 Degrees Celsius for 10 minutes. This wet chemical step oxidizes the top silicon layer and, in the process consumes silicon from the top surface. It is assumed that about 9 Angstroms of silicon is consumed. The surface oxide is removed in dilute HF (DHF). The EM-Probe and 4pp measurements are then repeated and the process continued until the desired depth is achieved. The EM-probe CV data are directly converted to active dopant density while the incremental R_S data are converted to carrier density with knowledge of the layer thickness and mobility.

APPLICATIONS

A study was made with varying Boron Implant species, with and without PAI and annealed with 650 Degrees C. SPE, 1000 and 1080 Degrees C. Spike anneal, 1300 Degrees C Flash anneal and Laser anneal. The expectations are that the µsec laser anneal should produce the highest implant dopant activation followed by the msec Flash anneal, sec. Spike anneal and SPE. Also, pre-amorphization enhances activation.

The N_{SURF} results of the B11 implant case are shown in Figure 3.

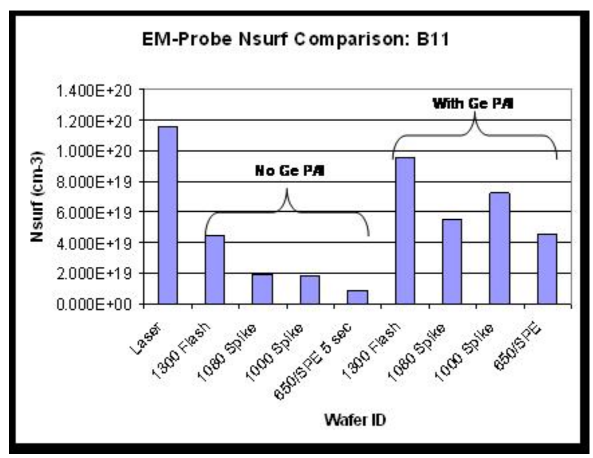


FIGURE 3. N_{SURF} results for B_{11} S/D Implant with the five anneals shown and with and without PAI. The measured N_{SURF} values in each case match the expected activation levels.

Several samples were selected and the Profiles verified by SRP and SIMS. In the case of the Laser annealed wafer shown above, incremental N_{SURF} and incremental 4pp R_S measurements were also made. The results of these atomic, active dopant and carrier density profiling methods are shown in Figure 4 for the laser annealed wafer.

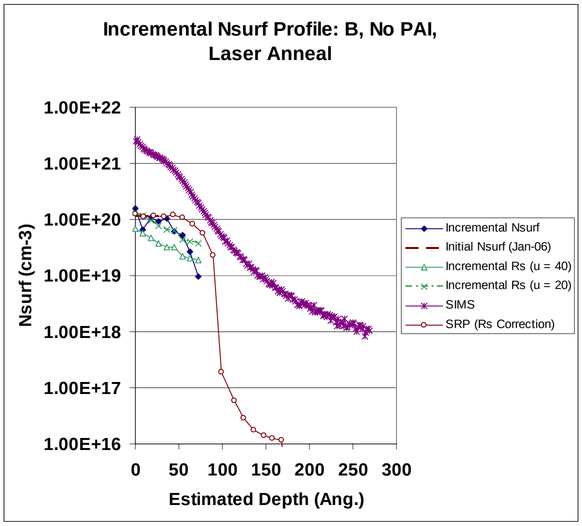


FIGURE 4. Profile Comparison: SIMS, SRP, Incremental CV (N_{SURF}) and Incremental 4pp R_S.

Although some noise is present in the incremental CV results, pretty close agreement with SRP at the surface exists. It is interesting to note that in order for the incremental 4pp results to match the CV and SRP results, a mobility of about a factor of two lower than the predicted bulk mobility must be used. This may be real and reflect the influence of surface damage due to the imperfect anneals and implant. The SIMS, which measures atomic or total dopant density (inactive) has a peak value of dopant density that is about a factor of ten higher. In the actual device, it is the electrically active dopants that matter.

In addition to annealing dependence, certain signatures can be identified and optimized by making EM-Probe N_{SURF} radial or diameter scans. Figure 5 is a plot of 4pp R_S and EM-probe N_{SURF} diameter scans obtained on a laser annealed wafer. A systematic or stitching effect can clearly be identified.

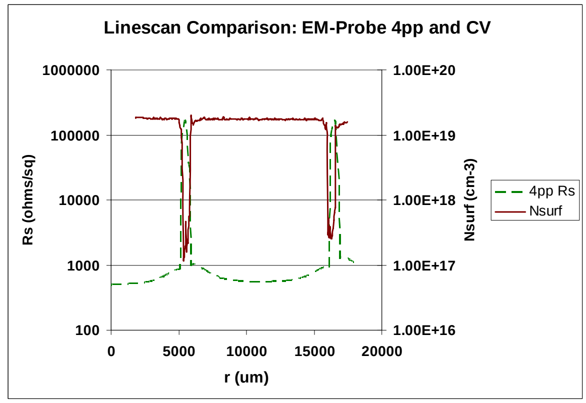


FIGURE 5. EM-Probe CV and 4pp R_S radial scans made on a laser annealed wafer piece.

SUMMARY

In this paper, a new CV based method for monitoring Implant activation was presented. The method described measures the electrically active near surface dopant density, N_{SURF}. Several example case studies were presented to demonstrate sensitivity. This method uses a non-penetrating and non-damaging elastic material Probe (EM-Probe) and has been used to measure 6 Angstrom gate dielectrics. It is therefore applicable for all current as well as future applications. Additionally, an active dopant profile can be obtained with the incremental methods described in this paper.

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