# Non-Contact SPV-based Method for Advanced Ion Implant Process Control

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## Abstract

Surface photo voltage (SPV) measurement has become an important semiconductor characterization tool due to the availability of commercial equipment and its non-contact nature. In this study, we discuss the application of the SPV technique for the control and monitoring of ion implanters, specifically for quantifying and qualifying lattice damage and electrically-activated dopants due to ion implantation in p-type CZ silicon. For as-implanted silicon, a measured SPV response includes the implant induced defect density and provides a photo-carrier lifetime; for annealed wafers, SPV measures the surface depletion layer charge of the activated dopants. Using the corona-charging technique and fine-tuning the wavelength and intensity of the probing light allows SPV to be successfully applied to a wide range of implant conditions.

In this study, the QC Solutions ICT-300® system (based on ac-SPV technology) is used for the monitoring and process control of 18 fab implanters. Seven production recipes are monitored daily, allowing process control to be managed within 2 percent accuracy.

The theory of small signal ac surface photo voltage and the principles of the technique are briefly discussed. A detailed explanation of the method and how it applies to implanter monitoring is provided. The ICT-300 system is used throughout the study to measure samples and collect presented data. The controlled processes reported are related to critical implant steps, including threshold adjust voltage, P well, and Halo implants. A detailed discussion of the threshold adjust voltage implant characterization and all pertinent aspects of the measurement process are presented.

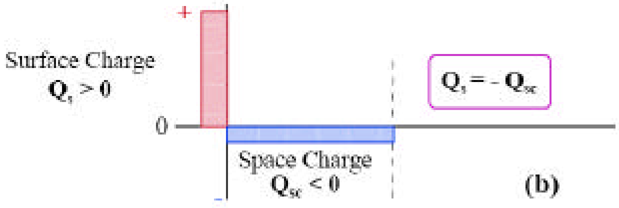
Keywords: surface photo voltage (SPV), ion implant, carrier lifetime

## I. Introduction

As CMOS technology continues to move rapidly towards decreasing feature sizes-, the role of ion implantation becomes increasingly important. Specifically, the formation of shallow junctions due to shrinking feature size makes high energy implantation critical to CMOS technology advancements—and substantiates the need for increasingly sophisticated metrology tools that can effectively monitor the implantation process. Methods providing direct information on the surface damage for as-implanted product wafers are attractive for process control. In this study, we show that surface photo voltage (SPV) is an effective in-line monitor for ion implantation of the most commonly implanted species. Using this technique, the reduction of bulk defects in current semiconductor production makes knowledge of the near-surface region easy to achieve. The SPV not only provides information about the damage induced on the lattice from the ion implant process, it can also map the effects of damage with a spatial resolution higher than other common monitoring tools .

## II. Theory of operation

When no electrical contact is made, the silicon surface remains in equilibrium with the bulk of the semiconductor. In this study, we define Qs (surface charge) and Qsc (surface space charge), and highlight that $Q_s = -Q_{sc}$ at thermal equilibrium (Figure 1). In the ICT-300 system, the electronic properties of the surface and near-surface region are determined by the measurement of the alternating current surface photo voltage (AC-SPV). The ICT-300 uses a simple, non-contact technique to measure the surface photo voltage ($V_{SPV}$). Correlating measured surface photo voltage to material parameters gives a value of a surface space charge $Q_{sc}$:



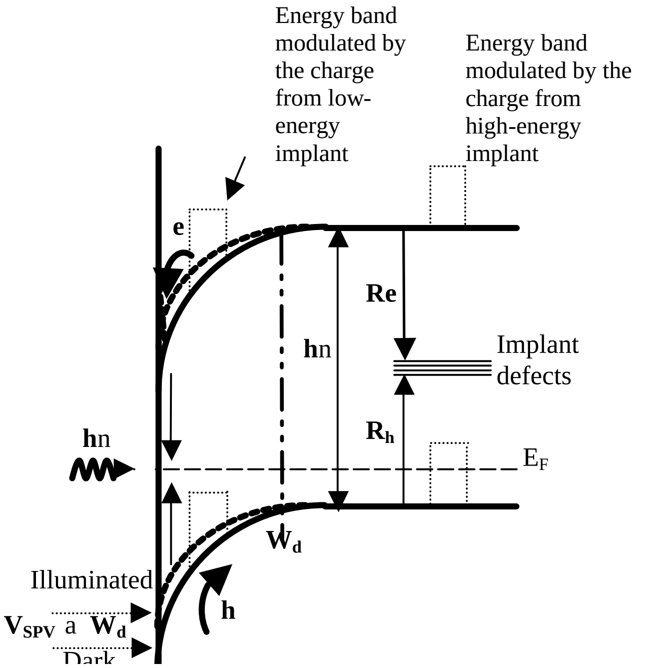


Figure 2 :Band diagram

$V_{spv} \approx \frac{kT\Phi}{Q_{sc}}\left(\frac{t}{1+iwt}\right)$, where T is temperature, Φ is a light flux, ω is a light modulation frequency and τ is a photocarrier lifetime.

Depending on the measurement regime, the SPV technique allows calculation of the doping concentration and surface recombination lifetime of a crystalline silicon wafer and the monitoring of the defect density of the implanted silicon wafer [1]. The variable best related to implant parameters is Qd (dynamic charge C/m$^3$) [3]. Qd is the charge density measured by the probe, and is related to the defect density induced during the implant process [2]. The ICT-300 is equipped with two light sources with different wave lengths (blue-light [BL] and ultra light [UL]) which allow the fine-tuning of measurement recipes for different implant conditions. The schematics depicting the corresponding changes of the energy bands at the semiconductor surface are shown in Figure 2.

In principle, the silicon surface is illuminated by a collimated beam of chopped light of photon energy greater than the silicon band gap. The light is absorbed close to the surface. The acquisition of the resulting SPV signal is achieved by means of capacitive coupling though an air gap. The implanted dose and energy is calculated by measuring the width of the surface depletion region, the surface recombination lifetime, and the variation of surface potential [1].

Table 1: Repeatability measurement on the same wafer (“golden wafer”). These values are the average and standard deviation of the measurement repeated each day on one wafer

| | |
|---|---|
| Mean | 18161,7371 |
| STD | 27,9025303 |
| STD% | 0,153% |

The resolution of the tool is adjustable between

| | |
|---|---|
| high: | 7854 points per wafer <=>4mm$^2$ each point |
| medium: | 1963 points per wafer <=>16mm$^2$ each point |
| low: | 491 points per wafer <=>64mm$^2$ each point |

## III. Process Control

Inline monitoring of the implanter not only verifies that it is performing inside the control limits, it also detects potential errors. This calls for daily monitoring of each implanter along with the development of at least one recipe for each implanter type (medium current, high current, high energy). The accuracy of this type of metrology tool is substantial. [3]

One characteristic of the ICT-300 is its sensitivity to a wide range of implant doses and energy. Therefore, instead of having to select a particular combination of specie and recipe that will maximize sensitivity, the implant recipes can be close to that used for production. For example, the dose sensitivity for B31Kev5E12 monitor is about 1.5 (calculated with %/% method). This means that for one percent of variation in dose, we have about a 1.5 percent variation in the Qd value.

To ensure high performance of the monitoring system, we made a daily qualification of the measurement machine using a set of “golden wafers.” Figure 3 shows partial results for repeatability tests on “golden wafer” implanted with boron11, at 31KeV, with a dose of 5E12/cm2.

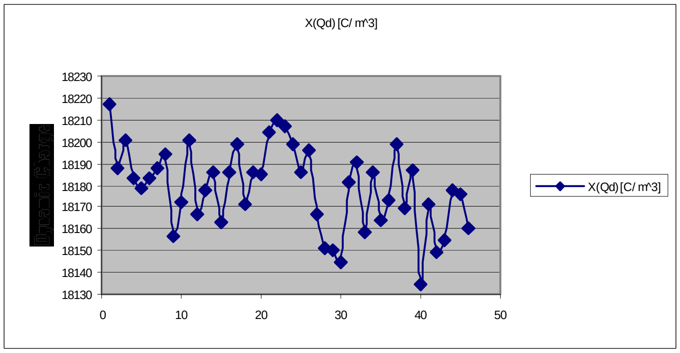


Figure 3: Repeatability test on “golden wafer” (B31K5E12)

The test was performed over a two-month period, with three measurements being taken each day. The final results are shown in Table 1.

In order to perform production control on implant steps, wafer fab, normally we use parametric structures to ensure that implanters are working correctly. Consequently, there are many days between the implant step and test step. The SPV method cannot be used on a production wafer, but can be useful for production control. When employed regularly, it can detect present problems on the implanter, and consequently future problem on the device. Figure 4 shows the control chart used for monitoring all implanters. The variability of the process itself is far more than the variability of the measurement tool, providing a powerful combination of sensitivity and repeatability.

From what has already been discussed, the benefits of this approach to process control are obvious. Dose sensitivity is beneficial not only to problems related to the dose controller, but is also helpful in detecting vacuum problems, especially with regards to leaks in a scanner section or in the end-station.

## IV. Angle Troubleshooting

A powerful characteristic of the ICT-300 is the ability to collect several hundred data points in one measurement cycle. These points can then be represented on a wafer map. With this map, the points can be easily viewed to determine if any pattern suggests trouble. Additionally, each implanter generally has a recognizable signature; thus it's possible to compare maps from each implanter to search for any relevant difference.

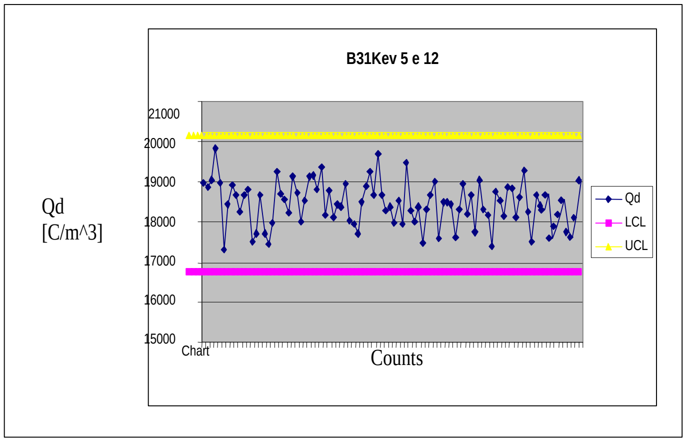


Figure 4: B31kev5E12 control chart. Each point represents an implanted wafer that was measured. From the entire process it is possible to calculate average and standard deviation, and set the control limits

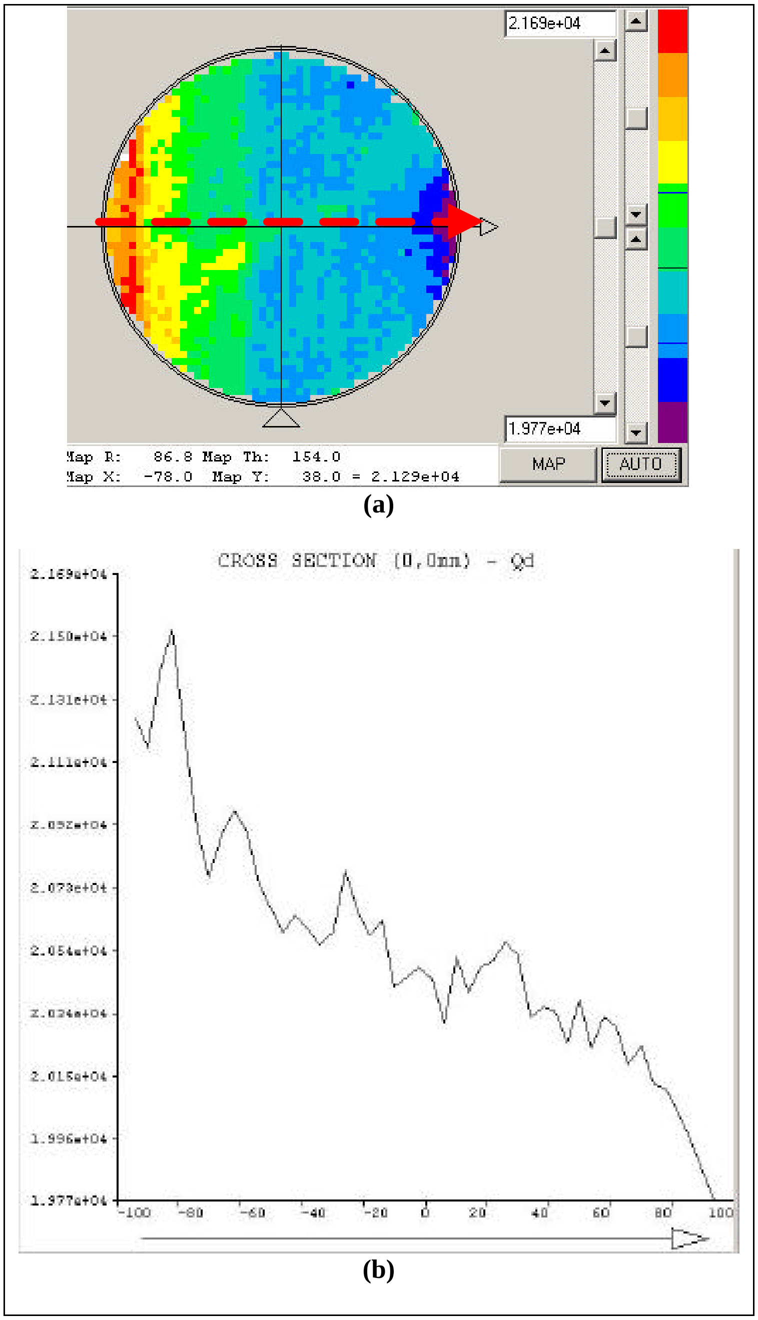
During implanter monitoring, we noticed that one implanter had a very particular map after maintenance. Also, the Qd value and Qd std (standard deviation calculated on Qd value measured on the wafer) had a value greater than the UCL (Upper Control Limit) of our control chart (see Table 2). The relevant change in mean and standard deviation is a clear sign of angle implant change. A misalignment of about 1.3 degrees in the implant position was found. If you compare these maps after the intervention, it's possible to see how the same signature is still present (see Figure 5 and 6), but the Qd value is aligned with the other implanter in both mean and STD. Of greater significance, however, is that the problem was solved before the implanter ran the production lots.

## SUMMARY

The significance of metrology to the implant process is evident. The QC Solutions ICT-300 system performs well both in repeatability and sensitivity, and can be easily used to verify the performance and stability of the implanter during production and after maintenance. Inline monitoring with SPV reduces error by highlighting problems before lots arrive at the end of the line. Although more than one process can be controlled for each type of implanter, it is the author's opinion that the most critical processes should be selected. Also, troubleshooting efficiencies are gained using all the parameters and software present on the ICT-300. Finally, sensitivity to dose, energy, and angle can be used to investigate the behavior of the dose controller, vacuum system, power supplies, and tilter head.

Table 2: Dynamic charge value before and after implant angle correction. It is possible to see how mean and standard deviation decrease after mechanical implant position correction

| Qd | Mean | STD |
|---|---|---|
| Before correction | 20550 | 331 |
| After correction | 18250 | 139 |

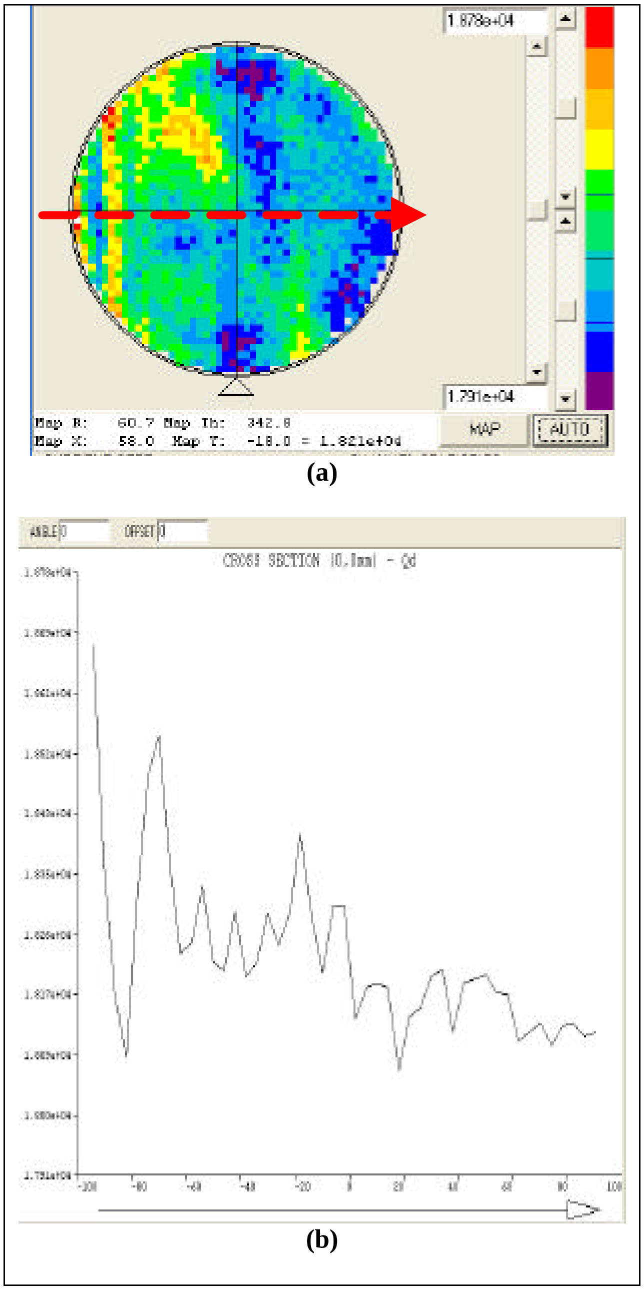


Map R: 86.8 Map Th: 154.0
Map X: -78.0 Map Y: 38.0 = 2.129e+04

(a)

(b)

Figure 5: Contour plot (a) and cross-section plot (b) of one measurement taken before angle correction. The cross-section shows the value of Qd for each point along the line that passes through the center of the wafer (see the red dotted line). It is possible to see how the Qd value changes from the left to right side.



Map R: 60.7 Map Th: 342.8
Map X: 58.0 Map Y: -18.0 = 1.821e+04

ANGLE 0
OFFSET 0

(a)

(b)

Figure 6: Contour Plot (a) and cross-section plot (b) of a measurement taken after angle correction. The cross-section shows the value of Qd for each point along the line that passes through the center of the wafer (see the red dotted line). After correction, there is a small residual difference of Qd between the left and right sides of the wafer

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2. Theory of Operation QC Solutions User Manual.
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AUTHOR BIOGRAPHY

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