

# Ion Implant Process Monitoring With A Dynamic Surface Photo-Charge Technique

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## Abstract

*A detailed parametric study was carried out over the course of approximately one year to determine the measurement sensitivity and repeatability of an in-line surface photo-charge metrology system for major implant parameters used in an established, high volume, 0.35mm CMOS process. The critical p-channel transistor implant processes; Threshold Voltage Adjust and Halo were used to characterize the metrology system. Dose variations as small as 1.5% have been measured with statistical accuracy, enabling improvements in process control to be quantified in real time. Long-term system repeatability of less than 1% (1σ) for a wide variety of implants has allowed the sensitive visibility of process drift or spike excursions to be highlighted in real-time.*

## INTRODUCTION

Ion implantation is one of the most challenging areas of semiconductor processing to monitor. Traditional measurement techniques allow for large to moderate changes in dose or energy to be detected, however, subtle changes may remain undetected until material reaches an in-line electrical test. In order to avoid costly negative yield impact, a highly sensitive, highly repeatable real time, in-line measurement tool is required.

A second-generation surface photo-charge technique has been developed as a viable tool for implant process monitoring in high volume integrated circuit manufacturing facilities. National Semiconductor Corporation (So. Portland, ME plant) and QC Solutions, Inc. (QCS) have worked together to generate sensitivity and repeatability data on a number of medium current, low dose implants. The sensitivities of dose, energy, beam current and implant angle of a typical boron ( $B^{11}$ ) Threshold Adjust implant ( $V_t$ ), as well as a typical arsenic ( $As^{75}$ ) Halo implant, are presented, along with repeatability data from gage studies performed with the

same implant conditions.

QCS implant measurements have three distinct areas of operation:

1. Medium energy, Low dose and Damage:

Implant conditions are typical of p-channel  $V_t$  adjust. The residual silicon crystalline structure is large enough that a surface charge barrier still exists and has to be taken into account in setting up the recipe. This region of implant conditions may require a corona charge application to invert the surface.

2. Low energy, High dose:

In this type of implant damage is severe but close to the surface, which influences the photo-charge primarily by surface lifetime reduction.

3. High Energy, Low dose:

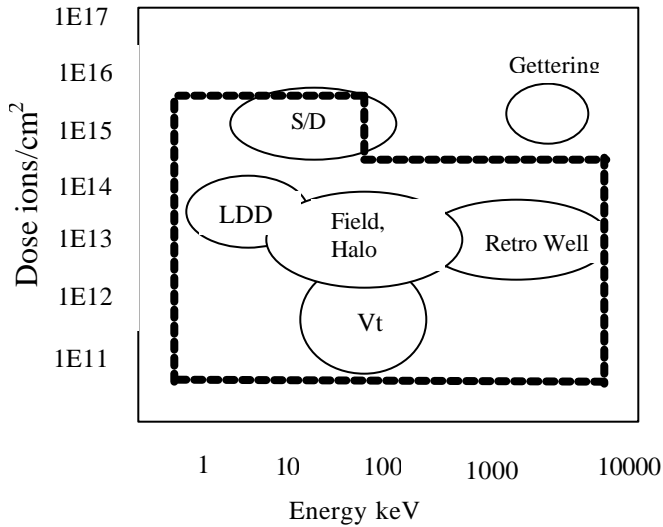
This type of implant is typical of retrograde wells, where there is a significant region of surface undamaged crystal. This case is lifetime dominated due to photo-charge trapping with in the bulk of the crystal

Implant crystal damage effectively reduces surface photo-charge through increased trapping. The strong influence on photo-carrier lifetime reduction from implant damage results in a net loss to the QCS signal, from that of undamaged silicon. It is this signal loss or difference that is used to measure relative changes in implant parameters.

The QCS surface photo charge technique has shown improved sensitivities to dose, energy, and beam current when compared to alternative implant metrology tools. High-density mapping allows across-wafer uniformity issues, resulting from subtleties in implanter hardware drift or excessive process control limits, to be identified and resolved. This can result in improved (within wafer) parametric die yield.

## EXPERIMENTAL

Typical ion implant dose/energy space for standard semiconductor processing can be divided in to six regions that require different measurement conditions. The enclosed dotted line in Figure 1 shows the operating range of the QCS tool.



**Figure 1: Operating range of QCS**

QCS options used to maximize sensitivity to the implants shown in Figure 1 are itemized in Table 1.

**Table 1: QCS measurement options**

Blue Light (BL)	$\lambda$ , 400nm operating depth in Si $\sim 1\mu\text{m}$
Ultra Light (UL)	$\lambda$ , 375nm operating depth inSi $\sim 0.1\mu\text{m}$
Corona	Line scan used to add charge to surface to further deplete to inversion. Positive or negative
Nsc	Depletion layer charge density
HdNsc	High crystal damage algorithm with reduced lifetime contribution - improves signal to noise ratio

Wafer conditions can be used to optimize the surface photo-voltage measurement for specific dose/energy regions. Essentially, the wafer type and surface oxide are the important factors. In cases where corona charge has to

be added, a 30Å thermal oxide is used to create a self-limiting charge condition.

**Table2: Optimum conditions for QCS**

### Implanted wafer condition

Implant Region/Species	Dose	Energy	Substrate Type	Optimum Surface
Vt B <sup>11</sup>	<5E13	10-100	P	<30Å
Vt P <sup>31</sup>	<1E13	10-100	N	<30Å
Vt As <sup>75</sup>	<5E12	10-100	N	<30Å
Field/Halo B <sup>11</sup>	5E13-5E14	10-150	N	Native
Field/Halo p <sup>31</sup>	1E13-5E14	10-150	P	Native
Field/Halo As <sup>75</sup>	5E12-1E14	10-150	P	Native
Ret Well B <sup>11</sup>	1E12-5E13	250-3000	P	<30Å
Ret Well P <sup>31</sup>	1E12-1E13	250-3000	N	<30Å
Ret Well As <sup>75</sup>	1E10-1E12	250-3000	N	<30Å
LDD B <sup>11</sup>	>1E14	0.1-5	N	None
LDD P <sup>31</sup>	>1E14	0.1 -5	P	None
LDD As <sup>75</sup>	>1E13	0.1-5	P	None

### QCS Measurement Recipe

Implant Region/Species	Corona	Light source	Measurement Algorithm
Vt B <sup>11</sup>	Positive	UL	Nsc
Vt P <sup>31</sup>	Negative	UL	Nsc
Vt As <sup>75</sup>	Negative	UL	Nsc
Field/Halo B <sup>11</sup>	None	UL	HdNsc
Field/Halo P <sup>31</sup>	None	BL	HdNsc
Field/Halo As <sup>75</sup>	None	BL	HdNsc
Ret Well B <sup>11</sup>	Positive	BL	Nsc
Ret Well P <sup>31</sup>	Negative	BL	Nsc
Ret Well As <sup>75</sup>	Negative	BL	Nsc
LDD B <sup>11</sup>	None	UL	Nsc
LDD P <sup>31</sup>	None	UL	Nsc
LDD As <sup>75</sup>	None	UL	Nsc

The results discussed are from two specific implants; Vtp adjust and a halo implant, for a 0.35µm CMOS process.

Vtp B<sup>11</sup>, 8.31E12, 10keV 7/33, 180µA

Halo As<sup>75</sup>, 2.61E13, 150keV 30/33, 250µA

Vtp implant substrate conditions were P type with 30Å thermal oxide. Halo implants were completed with P-type substrates. Wafers prepared with 30Å of thermal oxide were used, along with bare wafers (native oxide) to study the effects of wafer conditions. QCS conditions used in the measurements were:

Vtp: UL and Nsc (positive corona used if necessary)

Halo: BL and hdNsc

Variation of the following implant parameters were measured with full wafer mapping using standard resolution:

**Table 3: Parameter variation on Standard Implant Process**

	Vtp	Halo
Dose	±1,5,10%	±1,5,10%
Energy	±5,10,30%	±0,7,2,0,3,3%
Beam Current	±5,10%	±5,11,17%
Tilt	±14,28%	±3,3,6,7
Twist	±3,3,6,7%	±3,6%

**RESULTS**

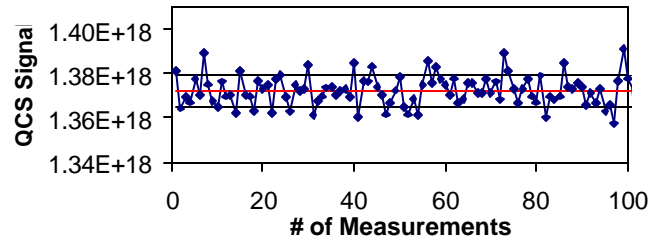
Mean values of medium resolution QCS wafer maps were used to achieve a linear fit (better than 0.9) of the five-point sensitivity data versus implant parameter (Table 4).

**Table 4: Sensitivity study for three case study implants**

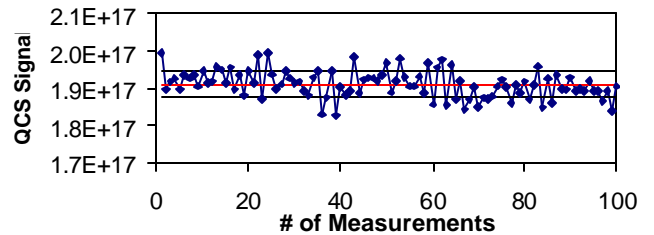
	Vtp (B <sup>11</sup> )	Halo (As <sup>75</sup> )
Dose	1.67	3.59
Energy	-0.62	4.07
Beam Current	0.19	0.23
Tilt	0.15	0.45
Twist	0.10	-0.28

Multiple repeatability measurements for the above implants were taken over three to four days. Temperature

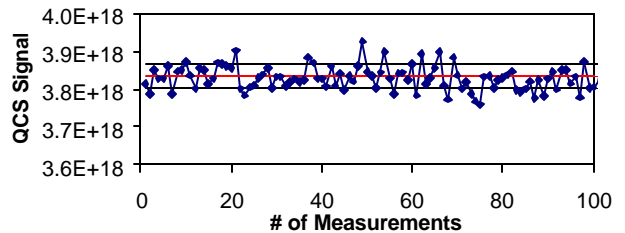
compensation was used to remove the effect of drift due to poor temperature control of the environment. Correction coefficients were calculated from the correlation of drift to temperature. Once the environmental effects were removed, the variation due to system random fluctuations alone was plotted.



**Figure 2: QCS Repeatability of Standard Vt Implant Wafer. Measured overnight. Trend mean 1.37E18, Trend Std Dev 0.50% (Dose Std Dev 0.3%)**

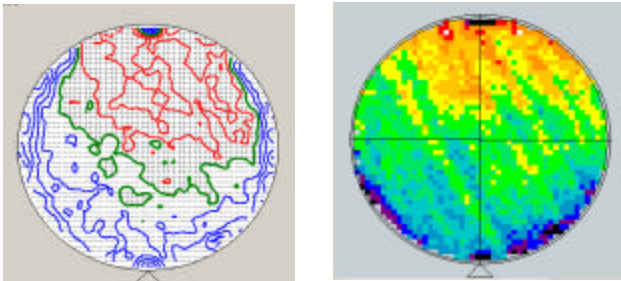


**Figure 3: QCS Repeatability of Standard Halo Implant Wafer. Measured overnight for three nights. Trend Mean 1.91E17cm<sup>-3</sup>, Trend Std Dev 1.92% (Dose Std Dev 0.53%)**



**Figure 4: QCS Repeatability of B11, 1E14, 100keV implanted Wafer. Measured overnight for three nights. Trend Mean 3.83E18, Trend Std Dev 0.85% (Dose Std Dev 0.24%)**

Wafer maps were generated in all cases. Figure 5 shows an example of high sensitivity and resolution mapping where the fast scan is not fully optimized leaving a striped pattern of high and low dose across a wafer.



**Figure 5: Typical Vt wafer maps (8.3E12 cm<sup>-2</sup>, 10keV) showing fast scan striping, more evident in color gradient map than in contour**

In the case of data measured from the Vtp implant; dose separation of 1.5% has been measured at 95% confidence level with daily measurements over a period of fourteen days.

## DISCUSSION

The wafer type requirements for optimized QCS measurement is more stringent for low dose implants, where the signal is not fully influenced by photo-carrier lifetime. In this regime an oxide of 30A is used to self limit (by current tunneling) the charge supplied during a corona application to invert the surface, creating a depletion layer. The polarity of corona charge applied is chosen to match the type of substrate e.g. positive – P type, negative – N type. Type of dopant is chosen to match substrate type. In general, QCS measurements of high dose implants are not so dependant on substrate type (or have corona requirements). Longer wavelength light has appeared to improve high dose measurement sensitivity. Light optimization may also lead toward increasing the frequency of modulation.

### Dose sensitivity

Experiments demonstrate a linear response with R<sup>2</sup> values greater than 0.97 as shown in Table 4.

The dose sensitivity noted of 1.67 to 3.59 for QCS surface photo-voltage measurements far surpasses the current low dose metrology for implant processing <sup>[1]</sup>. This strong sensitivity of QCS signal to implanted dose is caused by super-linear dependence of measured parameter, Nsc on inverse photo-carrier lifetime  $\langle t \rangle$ . In the case of heavy

crystal damage (e.g. high dose, large ion mass) this dependence can be reduced to a simple form <sup>[2]</sup>:

$$Nsc \propto \frac{m}{e^2 (aW_d)^2} \langle t \rangle^{-2}$$

Where  $\alpha$  is the light absorption coefficient and Wd is the depletion layer width, m is electron mass and e is electronic charge.

The lifetime of photo-generated carriers, in turn is inversely proportional to the level of damage or effective defect density.

This allows a very clear display of implant anomalies and effects that may need to be reduced for sensitive yield limiting implant steps.

### Energy sensitivity

Energy sensitivity shows both a positive and a negative dependence to QCS photo-voltage measurements. The negative energy dependence appears to be most prevalent where there is a large amount of silicon crystal left on the surface. That is typical of MeV implants or low dose, medium energy boron implants. Arsenic or ultra low energy implants appear to show mostly positive energy sensitivity. Such non-monotonous correlation of SCP signal to implant energy is consistent with the effect of QCS signal loss through lifetime reduction.

An implant damage profile combined with an in-depth distribution of photo-carriers (dependant on wavelength) will determine positive or negative implant energy dependence of SCP measurement, through drift and diffusion of photo-carriers to the implant generated trapping defects.

### Beam Current Sensitivity

Being very sensitive to crystal damage, QCS measurements are sensitive to implant beam current. It has been well established that implant damage results from two interactive rate effects: defect generation and defect annihilation during the implantation process. Implant parameters influencing the defect generation rate are implant species, dose rate and a weak dependence on energy. Factors influencing the annihilation rate are implant wafer chuck temperature, beam power, and wafer heat sink conditions. Given wafer temperatures, typical of medium current implanters, factors assisting defect generation predominate, resulting in a net increase of damage with beam current. Dynamic self-annealing (defect annihilation) becomes predominant at elevated implant temperatures.

### Implant Angle Sensitivity

QCS surface photo-voltage is less sensitive to angle tilt than dose, energy or beam current but still can be adequately measured in some cases, e.g. 0.45 for Halo

implant.

The combination of these parameters allows an implant process to be monitored by using the QCS signal as a “flag”. Statistical process control excursions are used as an indication of investigation required.

### **Repeatability**

Repeatability is typically “steady” to less than 1% one sigma for the QCS signal, ( 0.2 – 0.5% dose variability). A 30A oxide is used to passivate the crystal surface, providing optimum repeatability. Compensation for temperature effects on photo carrier generation in implanted wafers was applied to improve repeatability. It is expected and has been initially verified<sup>[3]</sup>, that wide use of temperature compensation would not be required in a typical fab environment, where temperature and humidity are closely controlled. Low dose separation of 1.5% can be measured with 95% confidence level over an extended period of time and a 1% dose separation can be observed within daily implants.

### **CONCLUSION**

Surface photo-charge measurements can be used to monitor ion implant processes for integrated circuit manufacturing, with improved sensitivity, allowing at a minimum, an early warning system of potential problems. Repeatable measurements provide an application to high volume silicon integrated circuit manufacturing, through statistical process control.

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