Photoelectric Measurement Method For Implanted Silicon: A Phenomenological Approach

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Abstract. A photoelectric method based on surface photovoltage effect (SPV) has been developed for monitoring of implanted silicon. A phenomenological model explaining major implant correlations has been proposed. The mechanisms for implant dose and energy sensitivities of the method have been identified.

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INTRODUCTION

The real-time fab metrology of implanted silicon is traditionally associated with the two techniques: optical reflectance measurement of crystalline damage for as-implanted silicon and electrical resistivity measurement (4pp) of annealed silicon. We have developed a non-contact photoelectric method [1] based on a surface photovoltage technique that allows measurement of both as-implanted and implant-annealed silicon wafers.

The surface photovoltage (SPV) effect is a well-established method that is used for measuring various semiconductor parameters, such as minority carrier lifetime, doping density, interface defect density, as well as for processing equipment characterization, such as furnace oxide quality, level of metal contamination, etc. Practically, all the SPV parameters are not measured directly, but are calculated from the measured characteristics using appropriate theoretical models and comparing the results to some reference values. Therefore, it is important to establish the proper theory and data analysis technique for this method. In general, the SPV phenomenon is based on two effects: 1) generation of electron hole pairs by light, 2) separation of the pairs by the surface electric field. In the depletion state, the minority carriers are collected at the surface changing surface potential and thus creating the SPV. We consider a small signal ac-SPV – a method where frequency modulated band-gap light only slightly changes the surface potential $V_{SPV} << kT$. The first theoretical description of this method for a uniformly doped semiconductor in inversion was done by Nakhmanson [2]. We present here a model for the SPV effect in ion-implanted semiconductor.

SPV IN IMPLANTED SILICON: THEORY

The frequency-dependent small signal SPV measurement is well understood for the single crystal semiconductor with the uniform doping. Charge on the wafer surface induces a space charge of the width W_d. Incident light with the energy higher than a band gap generates electron hole pairs in the space charge and neutral bulk regions, depending on the light wavelength. The lifetimes of generated photo-carriers depend on the recombination mechanisms. In a pure single crystal silicon photo-carriers recombine through the mid gap defects, pre-dominantly at the wafer surface. In high frequency regime, the measured photo-voltage is proportional to W_d that allows calculating surface charge in the depletion or doping concentration in the inversion state.

The implantation process introduces a large number of crystal defects that act as recombination centers for photo-generated electron hole pairs (see Fig.1). This high defect density affects the surface photo-voltage through reducing the photo-carrier lifetime: the larger the defect density the shorter the lifetime, therefore less photo-carriers reach the surface and the smaller is the SPV. Another effect of implantation process on the SPV phenomenon is a local modification of the energy bands due to the charge re-distribution in the implanted areas. This effect may be caused by the net charge of introduced defects or through trapping of majority photo-carriers by the implanted trap centers. In general, this effect is less important for the SPV analysis, with the exception of a few special cases, described later in the paper

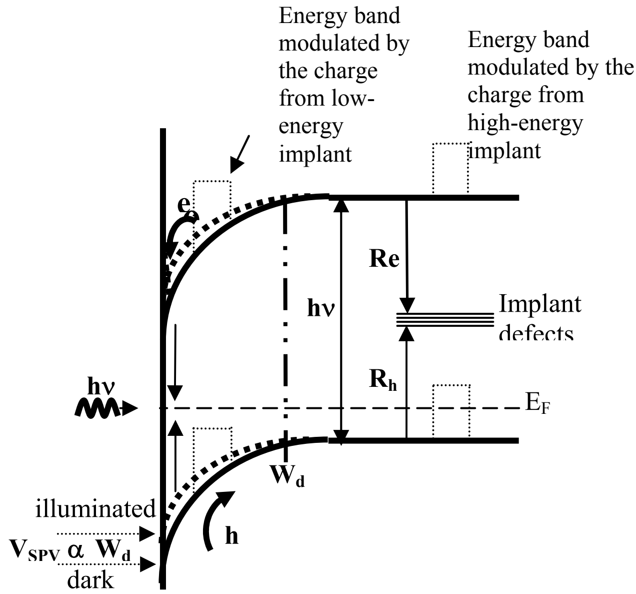

FIGURE 1. SPV band diagram of implanted p-type semiconductor in depletion; shows recombination through surface/space-charge states and through bulk implant defects

Equivalent Circuit

The standard set of differential equations describing the re-distribution of charge in semiconductor due to photo-excitation [2] can readily be analyzed with an equivalent electrical circuit.

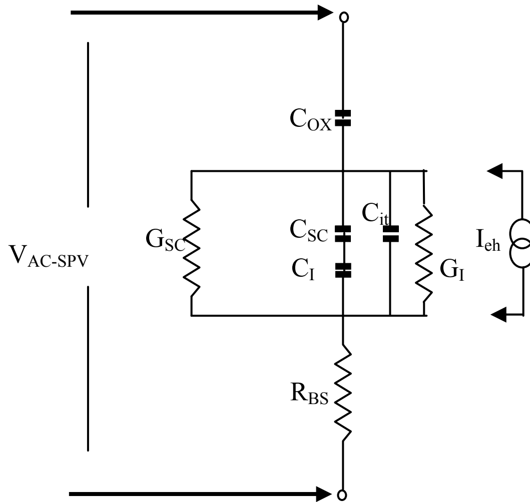

FIGURE 2. Equivalent electrical circuit of the SPV effect in semiconductor in full depletion with a contribution from implanted defects.

Conductance of the space charge region	G_{SC}
Capacitance of the space charge region	C_{SC}
Alternating photo current source	I_{eh}
Oxide capacitance	C_{OX}
Back contact series resistance	R_{BC}
Implant area conductance	G_I
Implant area capacitance	C_I
Interface charge capacitance	C_{it}

Figure 2, can be used to relate the capacitance and conductance to physical properties of the semiconductor, such as; doping density, carrier lifetimes, and defect density

From Figure 2 surface photo-voltage, V_{SPV} can be related to a familiar relationship [2]

$$V_{SPV}(\omega) = I_{eh}(\omega)\, Z_{eff}(\omega) \tag{1}$$

$$Z_{eff} = \frac{1}{G_{tot} + i\,\omega C_{tot}} \tag{2}$$

Where ω is a light modulation frequency, Z_{eff} is the effective impedance of the equivalent circuit, G_{tot} and C_{tot} are total conductance and capacitance of all contributing effects. At high frequency the oxide and interface traps capacitances can be neglected. The series resistance R_{BS} represent the majority carrier fast response and can be replaced by a short circuit, unless we deal with an intrinsic semiconductor. Further, in most practical cases the surface depletion layer width of the silicon substrates W_d used in IC processes (~1um) is much greater than implanted layer width (0.01-0.2um), that makes $C_I >> C_{SC}$, and therefore we have $C_{tot} \sim C_{SC}$. Also the recombination time of photo-carriers in the implant induced damage area is normally several orders of magnitude shorter than the lifetime in un-damaged space-charge region. As a result, the implant area conductance is much smaller than the space charge conductance, leading to further simplification $G_{tot} \sim G_I$.

Model

We present below a model of a small signal ac-SPV in implanted silicon for a case when the probing light absorption depth 1/α is greater than implant layer depth R_p. Other cases will be discussed qualitatively in the section on implant energy sensitivity.

It can be shown, that for low surface photovoltage $V_{SPV} < kT$, a relationship for the bulk (in our case implant area) conductance [3] reduces to:

$$G_I \approx \frac{q^2 n_i \Delta R}{\tau_{rec} kT} \tag{3}$$

with a characteristic recombination time

$$\tau_{rec} = \gamma^{-1} N_d^{-1} (kT/m)^{-1/2} \quad (4)$$

Here q is the elementary charge, n_i is an intrinsic carrier concentration, ΔR is an effective width of an implanted area, γ and m are a charge carrier capture cross section and an effective mass respectively, N_d is a concentration of defects-recombination centers.
Combining equations (1), (2) and (3) with a standard expression for space charge capacitance $C_{SC} \sim \varepsilon/W_d$, we find V_{SPV} to be:

$$V_{SPV} = \frac{I_{eh} W_d \tau_I}{(1 + i\omega\tau_I)\varepsilon} \quad (5)$$

With the implant area dominated lifetime given by:

$$\tau_I = \frac{kT}{q^2 n_i W_d \Delta R} \tau_{rec} \quad (6)$$

Where we assume the photocurrent density $I_{eh} \approx q\Phi$; Φ is the light flux density.
In the low frequency regime ($\omega\tau<1$) SPV measurement gives:

$$|V_{SPV}| \approx \frac{q\Phi W_d \tau_I}{\varepsilon} \quad (7)$$

which is a direct measure of photo-carrier lifetime τ_I influenced by implant defects.

To have a convenient measure of implant characteristics we introduce a new parameter -- dynamic charge Q_D that represents a charge in a depletion layer modulated by the photo-carrier response $\widetilde{W}_d = W_d \times (\omega\tau_I)$. From a standard Poisson equation, at full depletion condition a charge in the near surface region can be related to a depletion layer width:

$$Q_D \propto \frac{kT}{q\varepsilon \widetilde{W}_d^2} = \frac{q^3 n_i^2}{\varepsilon m \omega^2} (\gamma \Delta R N_d)^2 \quad (8)$$

Leading to a dependence of the introduced parameter Q_D to depend on the square of implant induced defect density and implant area width.

Ion Implant Measurement

To illustrate the SPV effect in implanted material the following experiment was performed: silicon samples were implanted with the ions of different mass and energy set to obtain similar depth profiles at constant dose. Figure 3 shows that the SPV measurement of as-implanted silicon is highly sensitive to the implant atomic mass or the amount of induced damage: approximately 7x variation of the AMU corresponds to about five orders of magnitude change in the dynamic charge Q_D value.

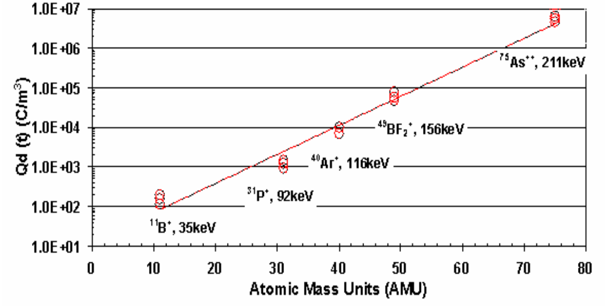

FIGURE 3. Sensitivity to implant damage/defect density at a constant dose of 6E13, with the same projected range of ~130nm [1].

Implant Dose Sensitivity

The mechanism of the SPV dependence on the implant dose is based on the straightforward relationship between the photo-carrier lifetime and the density of defects/recombination centers (6). Higher dose produces more defects that shortens the lifetime and reduces the photo-voltage signal. The SPV signal has monotonic behavior with respect to the dose up to the level of amorphization. Above the amorphization level the relevant lifetimes and the SPV measurement saturate, limiting the use of the method. Depending on other implant parameters affecting defect distribution – species, energy, tilt and implant temperature – the typical dose sensitivity factor is determined to be in the range from 1 to 3.

Implant Energy Sensitivity

The effect of the implant energy on the SPV measurement depends on the relationship of the damage profile and the probing light absorption. In the case described in a theory section, when the implant depth R_p is smaller than the absorption length 1/α, we find out from equations (5) and (6) that the photo-voltage is inversely proportional to the implanted area width ΔR, which is directly proportional to the implant energy. Thus, for all heavy implants or low energy light implants, the energy dependence of the calculated SPV parameter Q_D (8) has a monotonic behavior with a positive sign. (As^{75} implants with the energies < 200keVand B^{11} implants with the energy < 20keVare the examples of such measurement behavior, when the probing light wavelength is less than 0.5um.)

In case of the implant depth larger than 1/α, the energy dependence of the parameter Q_D has essentially non-monotonic behavior demonstrating first positive and later negative sign. To explain this energy dependence the non-uniform charge distribution,

associated with implant has to be taken into account. The analysis of the non-uniform charge profiles requires solution of differential equations for multi-layer model that is beyond the scope of this paper; here we give a qualitative explanation of the negative energy dependence phenomenon. With the increase of implant energy/depth beyond the light absorption length, all the electron-hole pairs are generated in the area between the surface and the implanted region. After the majority carriers reach the implanted region, part of them get trapped and change the potential barrier associated with the implant area (Fig.1). This charge layer screens the remaining portion of the depletion area (in case of $R_p<W_d$) or creates an additional charge area at a distance R from the surface (when $R_p>W_d$), thus effectively modulating a measured capacitance/depletion width. Now the photo-voltage becomes proportional to the implant depth R_p, which replaces W_d in equation (5). So, for higher energy implants this mechanism dominates and is mainly responsible for the reverse behavior of Q_D (E).

SPV Measurement of Annealed Silicon

The SPV measurement of the implanted and annealed silicon is essentially similar to the photo-voltage measurement of thin crystalline films [5]. The sequence of implantation and annealing processes creates a non-uniform doping profile in the near surface region that allows measurement of only an average value of the doping concentration. Due to the presence of several closely spaced and, in many cases, only partially depleted zones, the SPV measurement yields the net photo-voltage effect from one or more potential barriers. In case of the opposite doping types of implant and substrate (with the exception of ULE implants), the measurement result is highly inaccurate due to the compensating effects of the photocurrents oppositely directed at different barriers. So, normally SPV monitoring of annealed silicon requires same doping type of the implant and substrate that does not create additional p-n junctions. As it was mentioned earlier, the only exception is the ultra-low energy implants located within less than few nm from the surface. When implanted into the opposite doping type substrate, ULE implants make a very thin layer separated from the bulk by a potential barrier, resulting in a photovoltage signal dominated by the pn junction. One phenomenon characteristic to SPV measurement of ULE implants requires separate discussion. From Figure 4 one can see that a very distinct ring is visible at the edge of ULE wafer map.

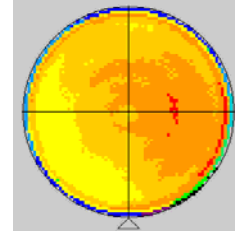

FIGURE 4. Typical wafer map of annealed ULE implant: B^{11} 0.5keV 1e15 implanted in n-type silicon substrate. The characteristic ring is due to the charge pile-up at the wafer edge.

Usually, for adequate explanation of major SPV related effects (strong inversion condition is one known exception) one-dimensional model is sufficient. This ring is an example of the case when a 3d modeling is required. Similar to the inversion layer, photo carriers in ULE area confined between the surface and p-n junction create lateral currents. Though, unlike the case of inversion, these lateral currents are formed by *majority* carriers, which have no other ways to move to the bulk because of the p-n junction presence. The majority carriers flow to the edges where the junction barrier can be lower due to the edge defects. The observed ring is clearly associated with build-up charge due to the major carriers piling up along the wafer edge.

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