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Improved Extraction of Si Substrate Parameters from Combined I-V and C-V Measurements on P-N Junction Diodes

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Abstract: Typical equations and methods used for years to analyse a p-n junction assume planar junction, so measured values are often treated just as volume values. Current components of I-V characteristics are sometimes extracted and analysed separately to determine their own parameters. However capacitance values from measured C-V characteristics are usually taken just as planar values and no extraction is done. The influence of combined capacitance and current components separation on p-n junction parameters and importance of capacitance components separation for accurate analyse of diode is shown for typical physical parameters used to characterise a p-n junction.

INTRODUCTION

From many points of view a simple p-n junction diode is a very useful test device for the characterisation and development of technological processes [1-3]. It is easy to process, its process contains most of the critical steps of modern CMOS technology and as a test structure it is sensitive to the relevant electrical yield detractors. Although p-n junction diodes are measured and analysed for decades, present-day needs require a more elaborate analysis of the data to yield relevant electrical information, e.g. from the peripheral diode regions. An important factor of influence on the electrical characteristics of diodes is the quality of the starting material. There have been considerable improvements over the last few years in silicon growth and thermal pretreatment. Effects that have not been detected under the cover of previously dominant components, or have been detected at more critical conditions (e.g. at elevated temperatures as diffusion component of reverse current), now often strongly influence typical electrical characteristics. At the same time beneficial influence of modern manufacturing thermal pretreatment, (e.g. intrinsic gettering effect of the oxygen related extended lattice defects), has simultaneously an undesired impact on electrical properties of silicon substrates, e.g. by the formation of thermal donors. Also shrinking dimensions of regions acting as p-n junction diodes in modern integrated circuits lead to an increased importance of peripheral effects (i.e. edge and corner related) as the perimeter-to-area (P/A) ratio increases.

Because typical equations and methods used for years to analyse a p-n junction assume a planar configuration, very often measured values are treated just as volume (planar) values. Even when an improved method is used to analyse a p-n junction, that should enable to separate diffusion current from generation current of a diode [1], no component values extraction is mentioned. On the other hand current components are more and more often extracted and analysed separately to determine their own parameters [2, 3]. However measured values from C-V characteristics are usually taken just as volume (planar) values and no geometrical correction is done.

To determine the influence of geometry of the device and defects formed in bulk lattice and in surface region of a p-n junction periphery on diode parameters, combined extraction of volume,

peripheral and parasitic components of C-V and I-V characteristics should be performed. It will be shown (especially for capacitance components) that such separation is very important for accurate analyses of typical physical parameters used to characterise a p-n junction, i.e. :
- type of junction (abrupt vs linearly graded) and doping concentration depth distribution;
- deep energy level (activation energy) determination from I-V temperature dependence,
- electric field influence on activation energy,
- carrier lifetime effective value and depth distributions from reverse I-V characteristics (τ_g - generation lifetime for depletion region, τ_r - so called recombination lifetime, for quasi-neutral bulk region).

EXPERIMENTAL

Diodes with different P/A ratio have been fabricated in p-type Si Cz substrates with various initial oxygen content (HO - high, LO - low) and thermal pre-treatments (IG - internal gettering, no - no pretreatment) as described previously [2]. Combined As and P ion implantation and furnace anneal are used, followed by a standard aluminum metallisation. The resulting junction depth is about 0.5 µm. Active regions are separated from each other by a relaxed LOCal Oxidation of Silicon (LOCOS) stack (750 nm thick field oxide).

HF C-V and static reverse I-V measurements were performed. Typically two area and two perimeter diodes are combined in a least-squares fit to extract separate volume, peripheral and parasitic capacitances and current densities. The junction reverse bias was varied from $V_J = 0$ V to 12 V, i.e. from small impact of the electric field to values for field-enhanced current generation.

RESULTS

Components separated from C-V and I-V characteristics of a diode are: C_{VOL} , C_{PER} - volume and peripheral capacitances; I_{VOL} , I_{PER} - volume and peripheral currents; $I_{VOLDIFF}$, $I_{PERDIFF}$ - volume and peripheral diffusion currents; C_{INTPAR} - internal parasitic capacitance. Measured values are labelled as: C_{MEAS} , I_{MEAS} .

The internal parasitic capacitance is typically a constant capacitance of metallisation paths, probing and mounting pads, bonding wires, etc. It increases for encapsulated devices but is non-zero for any measured diode, and is difficult to determine by direct measurements, in contrary to the external parasitic capacitance of the measurement set-up, that can be easily determined by direct measurements. Both parasitic capacitances can be extracted with good accuracy by a least-squares fit to the C-V characteristics of a diode array with different geometry. The instability of extracted parasitic capacitance when extraction enables it to change with the V_J changes, is a good measure of capacitance components extraction correctness. This instability for the presented results is less than 1 %.

When one of the current components is small in comparison with the others (as e.g. peripheral component for HO-no), the measurements need an excellent temperature stability, of the order of ± 0.1 K.

Even for large 900 µm x 900 µm diodes, differences among measured and separated values are distinguished in resulting parameters of junction. For a better visualisation, C-V and I-V characteristics for a 200 µm x 200 µm small junction were simulated for a HO-IG substrate (Fig.1 a, b). A C_{INTPAR} equal to a rather small value of 0.5 pF was chosen. It can be seen, that typically theinfluence of peripheral and parasitic components increases when V_J increases.

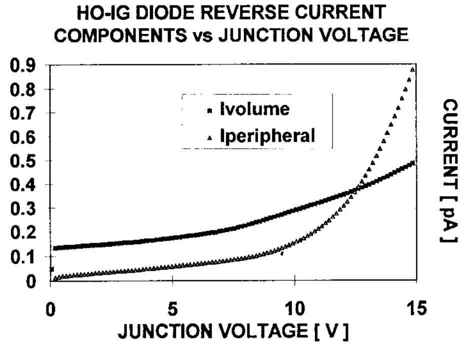
P-n junction capacitance in reverse direction was modelled by:

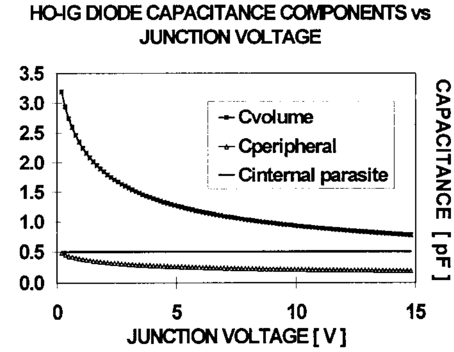
$$C_J = A\, C_{J0} / (1 - V_J / V_{bi})^{Mj} \qquad (1)$$

and the doping concentration distribution in substrate $N_A(x)$ was determined using the equation:

$$d(C_J^{-2}) / dV_J = [\, 2 / A^2 q \varepsilon N_A(x) \,] \qquad (2)$$

where: $V_{bi} = (kT/q) \ln(N_A N_D / n_i^2)$ is the built-in potential of the p-n junction, k - Boltzmann's constant, T - absolute temperature [K], N_A , N_D - doping concentrations on both sides of the junction, q - the electron charge, M_j - a parameter describing type of junction, equal to 1/2 for an abrupt and to 1/3 for a linearly graded junction, A - junction area, V_J - junction voltage and ε - silicon permittivity.





Figs. 1 a, b. Components of a HO-IG diode total current (from up to down: volume and peripheral) and capacitance (from up to down: volume, parasite and peripheral).

Fitting C_J for two sets of data: C_{MEAS} and C_{VOL} , yields values of C_{J0} , V_{bi} and M_j. For C_{MEAS} , parameter values obtained using (1) or (2), are (depending on substrate version) equal to: parameter M_j - from 0.36 to 0.40 (i.e. close to linearly graded junction), built-in voltage V_{bi} - from 0.45 to 0.55 V (surprisingly low), $N_{SUB}(x)$ - substrate doping concentration at depth 1.5 μm below the junction - from $4.7*10^{20}$ to $9.5*10^{20}$ [m^{-3}] and concentration change on next 2 μm depth - in the range from 54 to 89 %.

The same parameters for extracted characteristics of C_{VOL} was equal to: M_j - from 0.46 to 0.50 (i.e. very close to abrupt junction), V_{bi} - from 0.58 V to 0.67 V, doping concentration - from $3.5*10^{20}$ to $7.5*10^{20}$ [m^{-3}] and concentration change - from 2 to 17 %.

So not taking into account junction capacitance components for abrupt and almost uniformly substrate (base) doped p-n junction with typical built-in voltage, presents it as almost linearly graded and strongly nonuniformly doped junction with higher than in reality base (substrate) doping but simultanously with very low built-in voltage (Fig. 2).

Because the depletion region width W_d is also connected with C_J by the equation:

$$C_J = A\,\varepsilon / W_d \qquad (3)$$

so these differences between C_{MEAS} and C_{VOL} characteristics influence many p-n junction parameters, substantially through W_d , N_{SUB} (x) and V_{bi} changes. Of course, an accurate determination of junction parameters requests also current components separation. But taking C_{VOL} instead of C_{MEAS} seems to be uncommon, while taking into account components of current is more popular.

The diffusion current for the volume component $I_{VOLDIFF}$ is determined using a plot I_{VOL} vs $(W_d)^{1/2}$ [1]. $I_{VOLDIFF}$ is the value at the intersection of straight line with the y-axis at $W_d = 0$.

Values of C_{MEAS} make different (typically - smaller) W_d than for C_{VOL}, and different (typically - higher) value of $I_{VOLDIFF}$.

The value of $I_{VOLDIFF}$ can be used to obtain the effective recombination lifetime in the substrate quasi-neutral region using equation for asymetrical junction:

$$I_{VOLDIFF} = Aqn_i^2 (D_n / \tau_r)^{1/2} / N_A \qquad (4A)$$

$$\tau_r = A^2 q^2 n_i^4 D_n / (I^2_{VOLDIFF} N_A^2) \qquad (4B)$$

where n_i - intrinsic carrier concentration, D_n - minority carriers effective diffusion coefficient and τ_r - recombination lifetime in quasi-neutral substrate with effective doping density N_A. The recombination lifetime value depends strongly on n_i value taken for calculations [4,5].

Because for C_{MEAS} both $I_{VOLDIFF}$ and N_A are different from values for C_{VOL} characteristics (D_n difference is much smaller), the obtained effective lifetime τ_r increased or decreased depending on many variables, as parasitic to peripheral junction capacitances ratio, etc.

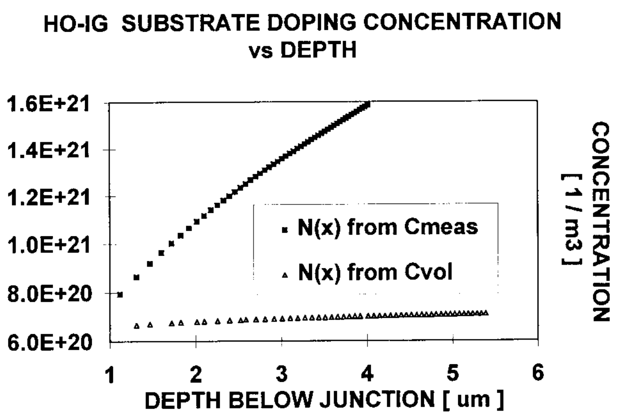


Fig.2. Comparison of substrate doping concentrations obtained for HO-IG substrate version using (from up to down) C_{MEAS} and C_{VOL}.

These values of $I_{VOLDIFF}$ determined for different temperatures plotted vs inverse temperature 1/T can be used to determine the activation energy of the diffusion current (Fig. 3). This plot is a good measure of current components accuracy, as this activation energy should be equal to the energy gap E_g. This value for presented results is (within 3 % accuracy) the silicon E_g for that range of temperatures.

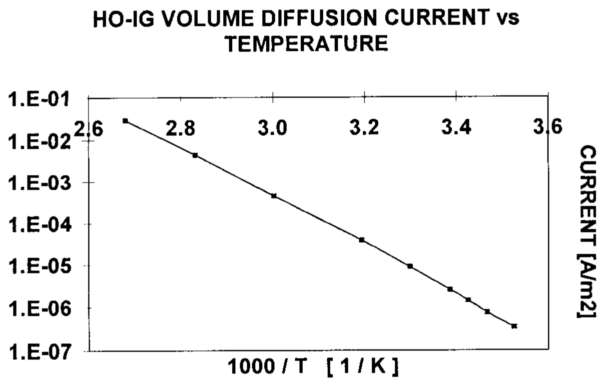


Fig.3. Temperature dependence of the volume diffusion component for the HO-IG diode.

The difference of the total volume current component and the diffusion current of volume component gives the generation current of volume component. The temperature dependence of this current allows to determine an activation energy (and deep energy level) for that component (Fig. 4). Using this value the source of defects responsible for the generation leakage current can be identified in many cases. With incorrect $I_{VOLDIFF}$, activation energies can not be accurately determined.

The current generation is enhanced by the electric field. In first instance, the Poole-Frenkel effect should be taken into account. Furthermore, other effects like trap-assisted tunneling can play a role. The investigation of the field effect requires a proper generation current value and proper electric field F vs V_J dependence. The optimised method needs taking into account the electric field value at any point in the depletion region, but typically, the dependence on so-called maximum electric field is analysed [6]:

$$F_{MAX} = K_j \left[(V_{bi} + V_J) / W_d \right] \quad (5)$$

, where the parameter K_j depends on the type of junction - for abrupt junction is equal to 2, for linearly graded junction is equal to 3/2. .

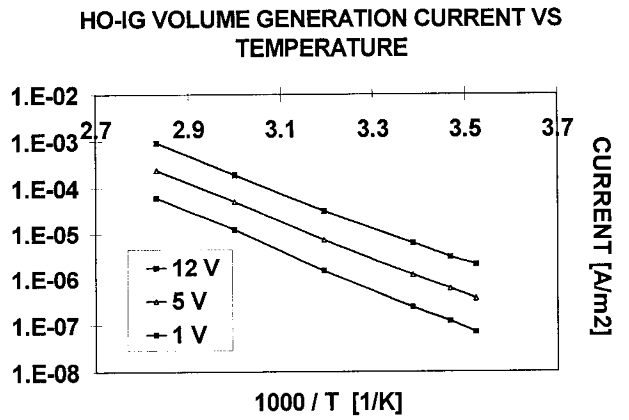


Fig. 4. Temperature dependence of the volume generation component for the HO-IG diode (V_J is from up to down: 12 V, 5 V and 1 V).

So using C_{MEAS} instead of C_{VOL} changes not only the $I_{VOLDIFF}$ value, but also K_j - type of junction parameter (K_j change results from fitting Eq.1), V_{bi} and W_d . These changes influence the activation energy vs F_{MAX} dependence (Fig. 5).

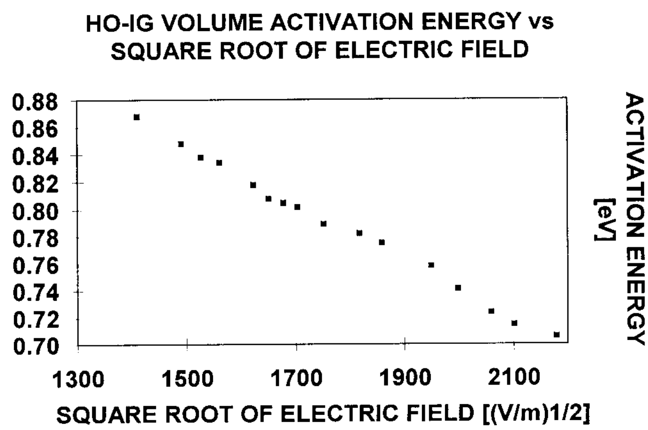


Fig. 5. Activation energy of the volume generation current for the HO-IG diode vs the square root of the maximum field in the junction.

The decrease of the activation energy with the square root of electric field for the Poole-Frenkel effect is described by lowering the barrier energy of emission over the potential barrer by a quantity ΔE [6]:

$$\Delta E = (q^3 F / \Pi \varepsilon)^{1/2} \quad (6)$$

For the Poole-Frenkel mechanism in Si, one obtains $\Delta E = 3.55 \; 10^{-24}$ [J $m^{1/2}$ V $^{-1/2}$] times $(F)^{1/2}$. For the dependence shown in Fig. 5, the coefficient is about ten times more, so not only Poole-Frenkel effect occurs in these HO-IG samples.

Depth distribution of carrier generation lifetime $\tau_g(x)$ was counted using equation:

$$\tau_g(x) = Aq \, n_i \, / \, (dI_J / dW_d) \quad (7)$$

for three sets of data: C_{VOL} and I_{VOL} , C_{MEAS} and I_{VOL} , C_{MEAS} and I_{MEAS} (Fig. 6). The biggest values of lifetimes and most uniform lifetime distribution are for C_{VOL} and I_{VOL} set of data.

If the ratio of electron σ_n and hole σ_p capture cross sections for the center do not differ too much, the dependence between τ_r and τ_g can be written as [7]:

$$\tau_g = 2\, \tau_r\, (\sigma_n / \sigma_p)^{1/2} \cosh [(E_T - E_i) / kT] \quad (8)$$

and sometimes is written as [8]:

$$\tau_g = \tau_r \exp [(|E_T - E_i|) / kT] \quad (9)$$

where $E_T - E_i$ is the difference between the energy of the center and the intrinsic energy levels.

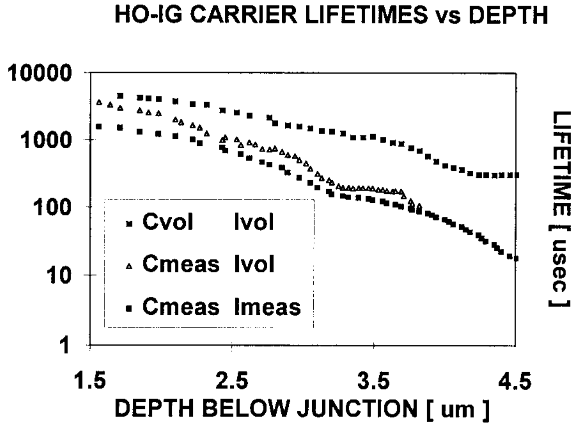


Fig. 6. Depth distribution of carrier generation lifetime for three sets of data (from up to down): C_{VOL} and I_{VOL} ,C_{MEAS} and I_{VOL} , C_{MEAS} and I_{MEAS} .

Using Eq.9 for determined τ_r (Eq.4B and Fig.3) and for τ_g at small depths - i.e. for small electric fields - (Fig. 6), gives $E_T - E_i$ value equal to 0.30 eV for HO-IG. This is in good agreement with the HO-IG activation energy for volume generation component determined at small electric fields, which is 0.87 eV (Fig.5). The corresponding activation energy for the HO-IG perimeter generation component is 0.68 eV.

Values of τ_g taken deeper in substrate are connected with a larger electric field. Because the field enhances emission (Eq.6), it should also influences $\tau_g(x)$ given by the Eq.7. When τ_g vs depth dependence is transformed into τ_g vs F_{MAX} dependence, the activation energy vs F_{MAX} dependence can be used for normalisation (multiplication) of $\tau_g(x)$ to values at small electric field. When typical HO-no τ_g vs depth dependence [2] is subjected to such normalisation using activation energy vs F_{MAX} dependence [9], almost uniform $\tau_g(x)$ depth distribution for HO-no is obtained. It is also in agreement with the conclusion in [1], that usually τ_g vs electric field is the substantial dependence of τ_g , and the τ_g vs depth dependence is often a secondary effect.

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