Improved extraction of the activation energy of the leakage current in silicon *p–n* junction diodes

A. Poyai,[a),b)] E. Simoen, and C. Claeys[a)]
IMEC, Kapeldreef 75, B-3001 Leuven, Belgium

A. Czerwinski
Institute of Electron Technology, Al. Lotnikow 32/46, 02-668 Warsaw, Poland

E. Gaubas
Vilnius University, Institute of Material Research and Applied Sciences, Sauletekio av. 10, LT-2040 Vilnius, Lithuania

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An accurate method is proposed for the extraction of the activation energy E_T from the volume generation current density J_{gA} in silicon $p-n$ junctions. It combines temperature-dependent current–voltage ($I-V$) and capacitance–voltage measurements on an array of diodes with different geometry, in order to separate the peripheral from the volume components. The J_{gA} can be found from the volume leakage current by subtraction of the volume diffusion current J_{dA}, which is calculated from the forward $I-V$ characteristic. To derive the correct slope from an Arrhenius plot of the J_{gA}, several additional corrections have been applied. One is the temperature dependence of the depletion width, which is derived from the corrected volume capacitance. The most important E_T change is shown to come from the temperature dependence of the recombination lifetime. [DOI: 10.1063/1.1359487]

The requirements for present-day high-quality silicon substrates are extremely tight with respect to the control of grown-in or processing induced defects. Yet, there may still be a marked effect of the starting material on the electrical characteristics of simple device structures, like a capacitor or a $p-n$ junction. In other words, such devices can be used as tools, which reveal relevant information on the electrical activity of defects. For example, it is possible to extract the recombination τ_r and generation τ_g lifetime from the forward and reverse diode characteristic, respectively.[1,2] The ratio τ_g/τ_r yields in principle the energy level with respect to mid gap, i.e., $|E_T-E_i|$ of the dominant generation-recombination (GR) center, according to the relationship[3,4]

$$\tau_g=\tau_r \exp\left(\frac{|E_T-E_i|}{kT}\right) \qquad (1)$$

for E_T more than a few kT away from E_i, with E_T the energy level of the GR center and E_i the intrinsic Fermi level at about 0.56 eV from the silicon band edges at 300 K; k is the Boltzmann constant and T the absolute temperature. Another way to yield information on the energy level of the generation centers in the depletion region of a diode is to study the reverse current I_R as a function of temperature. E_T is usually derived from the slope of an Arrhenius plot of $\ln(I_R)$ versus $1/kT$, whereby only the exponential $1/T$ dependence is taken into account. It will be demonstrated here that in order to derive an accurate E_T, one should consider the temperature dependence of all factors determining the J_{gA}.

For this study, n^+-p diodes have been processed on Czochralski (Cz) and epitaxial (epi) grown wafers in a 0.35 μm complementary metal–oxide–semiconductor compatible technology, using a 70 keV arsenic ion implantation with a dose of $3\times10^{15}\,\mathrm{cm}^{-2}$, followed by an 1100 °C 10 s rapid thermal anneal. This results in a junction depth of around 0.2 μm. Standard local oxidation of silicon (LOCOS) is used to define the active regions, while Al metallization is applied as contact material to the front n^+ and back p electrode. Before diode processing, a high–low internal gettering (IG) pretreatment is applied to the Cz wafer, consisting of an oxygen outdiffusion step of 6 h at 1100 °C under nitrogen, followed by an 8 h 750 °C nucleation step. The third step in the IG cycle is the high temperature oxidation of the LOCOS fabrication. Junctions with different geometry have been studied in order to separate volume J_A, peripheral J_P, and corner J_C current and capacitance components, using the procedure reported elsewhere.[5,6]

The current–voltage characteristics of the diodes were measured on a wafer, in the dark, in the range of −5 to +1 V, whereby the bias was applied to the back p-type substrate and the current measured at the grounded top n^+ contact. A holding time of 120 s was used to obtain a steady-state reverse current. This was needed to suppress light-induced transients for the largest diodes in Cz substrates, as reported previously.[7] Temperature dependent measurements were done in the range 25–120 °C, allowing extraction of the E_T of the reverse current density. Capacitance–voltage measurements were performed on the same diodes at a frequency of 100 kHz, as a function of temperature, to extract the volume depletion width W_A, according to the method described earlier,[5] and the doping density in the substrate N_A.

[a)]Also at KU Leuven, E.E. Department.
[b)]Author to whom correspondence should be addressed; electronic mail: amporn@imec.be

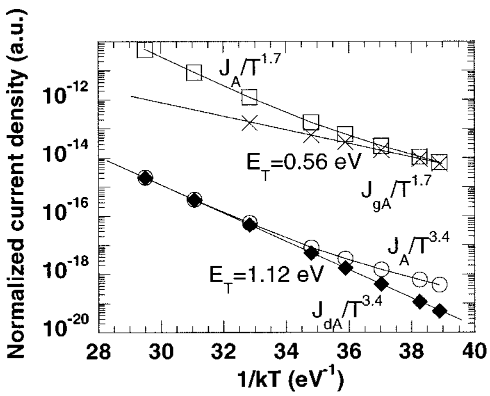

FIG. 1. Arrhenius plot constructed with normalized $J_A/T^{3.4}$, $J_A/T^{1.7}$, $J_{dA}/T^{3.4}$, and $J_{gA}/T^{1.7}$.

The J_A derived from the geometric separation consists of the sum of J_{dA} and J_{gA}. The J_{dA} and J_{gA} in an n^+-p diode can be written as follows:

$$J_{dA}=qn_i^2\frac{D_n}{L_nN_A}, \tag{2}$$

$$J_{gA}=\frac{qn_iW_A}{\tau_g}, \tag{3}$$

where q is elementary charge, n_i the intrinsic carrier concentration, D_n the diffusion coefficient of electrons in the p side, and $L_n=\sqrt{D_n\tau_r}$ is the electron diffusion length. In writing Eq. (2), it is assumed that the contribution of the hole diffusion current in the n^+ layer can be neglected, which is the case here. In addition, Eq. (3) is only valid if electric field assisted thermal generation or trap-assisted tunneling can be neglected. This has been verified experimentally,[6] showing a $\sqrt{V_R+V_{\rm bi}}$ bias dependence of the current density, where $V_{\rm bi}$ is the built-in potential.

One way to separate the two physical components, described by Eqs. (2) and (3), is by studying the temperature dependence of the leakage current. By considering the experimental n_i obtained by Sproul and Green[8]

$$n_i=1.640\times10^{15}T^{1.706}\exp\left(-\frac{E_g}{2kT}\right) \tag{4}$$

and substituting Eq. (4) in Eq. (2), the temperature dependence of the J_{dA} should be given by

$$J_{dA}\propto T^{3.4+\gamma}\exp\left(-\frac{E_g}{kT}\right), \tag{5}$$

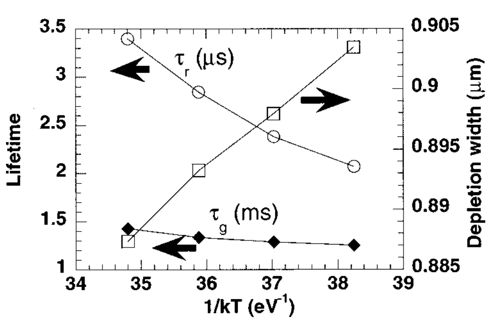

FIG. 2. Recombination and generation lifetime (left axis) and depletion width (right axis) vs temperature.

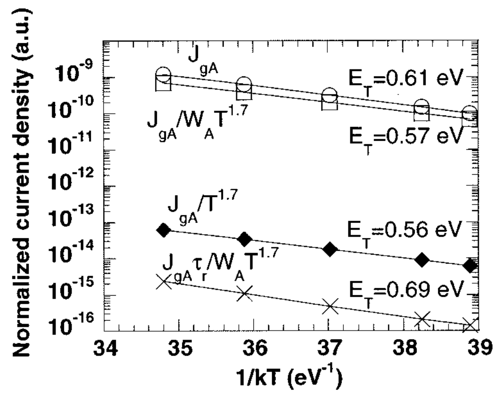

FIG. 3. Arrhenius plot constructed with normalized J_{gA}, $J_{gA}/T^{1.7}$, $J_{gA}/W_AT^{1.7}$, and $J_{gA}\tau_r/W_AT^{1.7}$ parameters.

where E_g is the band gap of silicon ($\sim$1.12 eV at 300 K) and γ is a small number (<1) related to the temperature dependence of the minority carrier mobility and the diffusion length. On the other hand, by substituting Eqs. (1) and (4) into Eq. (3) and assuming $E_i=E_g/2$, the temperature variation of the J_{gA} for the GR energy level in the upper half of the band gap becomes

$$J_{gA}\propto\frac{T^{1.7}W_A}{\tau_r}\exp\left(-\frac{E_T}{kT}\right). \tag{6}$$

Since E_T is smaller than E_g, it is clear from comparing Eqs. (5) and (6) that an Arrhenius plot of J_A versus $1/kT$ yields a slope $-E_T$ at lower temperatures and $-E_g$ at higher temperatures. However, according to Eqs. (5) and (6) it is better to use J_A normalized by $T^{3.4}$ or by $T^{1.7}$, in order to extract E_g or E_T, as shown in Fig. 1. There, it becomes immediately clear that the extraction of E_T from the low-temperature part of the curve is not straightforward and affected by the J_{dA}. A value of 0.77 eV has been reported,[6] which overestimates the true activation energy, due to the contribution of the J_{dA}. This is even more so, if no $T^{1.7}$ normalization is carried out.

The J_{dA} can be alternatively derived from the forward-current intercept, as outlined previously,[9] whereby the ideality factor is taken into account. As a first improvement, it is proposed here to use the J_{gA}, given by J_A-J_{dA} instead of J_A for the construction of an Arrhenius plot. As shown in Fig. 1, this leads to a value of 1.12 and 0.56 eV for E_g and E_T, respectively. The experimental E_g is close to the value expected from theory. This shows that the γ in Eq. (5) is neg-

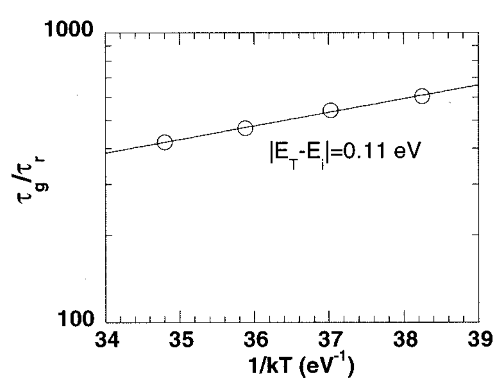

FIG. 4. Arrhenius plot of the generation/recombination lifetime ratio.

TABLE I. E_g, E_T obtained from different normalized current densities and $|E_T - E_i|$ values for diodes processed in epitaxial (epi) and Czochralski (Cz) wafers, respectively.

Wafer	$E_g(J_{dA}/T^{3.4})$ (eV)	$E_T(J_{gA})$ (eV)	$E_T(J_{gA}/T^{1.7})$ (eV)	$E_T(J_{gA}/W_A T^{1.7})$ (eV)	$E_T(J_{gA}\tau_r/W_A T^{1.7})$ (eV)	$\|E_T - E_i\|(\tau_g/\tau_r)$ (eV)
Epi	1.08	0.65	0.61	0.61	0.90	0.30
Cz	1.12	0.61	0.56	0.57	0.69	0.11

ligibly small. On the other hand, replacing J_A by J_{gA} has a strong impact on the obtained E_T, lowering it from 0.77 to 0.56 eV. It should be remarked in this respect that $J_{dA}(V_R)$ is not necessarily equal to J_{dA} at zero bias (intercept value).[10] However, it has been found that the bias dependence of the diffusion current is small (on the order of 2%–3%), so that this effect can be neglected here.

So far, the temperature dependence of W_A and τ_r in Eq. (6) has been neglected. As can be seen from Fig. 2, W_A reduces for increasing temperature, mainly through a reduction of V_{bi} with T. W_A can be derived accurately by separating the volume capacitance C_A from the peripheral C_P and the corner C_C capacitance, leading to $W_A = \varepsilon_{Si}/C_A$,[5] where ε_{Si} is the semiconductor permittivity. The τ_r, on the other hand, enhances with temperature.[8] The temperature dependence of τ_r follows from the experimental forward-current intercept and from Eq. (2), whereby the temperature dependence of Ref. 11 for D_n is substituted. The τ_g, derived from Eq. (3), is in the investigated interval nearly constant with temperature.

Figure 3 summarizes the effect of the different temperature corrections on the activation (or trap) energy from an Arrhenius plot. The values for E_T obtained for a normalized volume generation current density given by J_{gA}, $J_{gA}/T^{1.7}$, $J_{gA}/W_A T^{1.7}$, and $J_{gA}\tau_r/W_A T^{1.7}$, are 0.61, 0.56, 0.57, and 0.69 eV, respectively. From these data follows that the strongest effect stems from the temperature dependence of τ_r, while the impact of W_A or even $T^{1.7}$ is rather small. Note also that the final value (0.69 eV), taking all temperature effects into account, is again closer to the uncorrected value of 0.77 eV.

The obvious question arises: which of the obtained E_Ts is the most correct one? One way of tackling this issue is by an independent evaluation of E_T using a different technique. Unfortunately, deep level transient spectroscopy does not reveal any deep level within the sensitivity of the technique. On the other hand, cross-sectional microwave absorption (MWA) measurements of the recombination lifetime give values which are in reasonable agreement with the τ_r's derived from the forward diode characteristic.[12] MWA analysis as a function of temperature shows activation energies in the range $0.08 \pm 0.02 - 0.16 \pm 0.05$ eV, which is close to the activation energy of τ_r found here (Fig. 4). In Fig. 4, the ratio τ_g/τ_r is represented, which, according to Eq. (1) should yield $|E_T - E_i|$. By considering that $E_i = 0.56$ eV at 25 °C, an $E_T = 0.67$ eV is expected. This value is close to the one that is obtained from the slope of the Arrhenius plot for the normalized parameter $J_{gA}\tau_r/W_A T^{1.7}$. In addition, similar values for $|E_T - E_i|$ have been obtained in the past for diodes in *p*-type Cz silicon substrates.[1] This procedure has also been applied for diodes on epitaxial (epi) wafers as shown in Table I. It can be noticed from the last two columns that in both cases the accuracy is within 20%. A final comment which needs to be made is that E_T extracted in this way has to be considered as an effective or weighed energy level, which does not necessarily correspond to a real trap level.

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