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APPLICATION OF OPEN CIRCUIT VOLTAGE DECAY TO THE CHARACTERIZATION OF EPITAXIAL LAYER

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High quality silicon epitaxial layers are inevitable in bipolar and/or unipolar technology. However, their properties are not as easy characterized as those of bulk material. The recombination lifetime is dominated by surface/interface recombination for thin layers, which epitaxial ones generally are. We have designed a diode structure with n^+np^+ and p^+pn^+ epitaxial layers for the open circuit voltage decay (OCVD) technique. In such a structure injected carriers are constrained within the lightly doped base by potential barriers of the junction and high-low contact and their concentration can then decrease only by recombination. Performing OCVD measurement for high-level injection condition, also τ_n and τ_p could be evaluated. The carrier lifetime obtained in this manner yields information mainly about the defect properties of the epitaxial layer, nevertheless, surface/interface recombination can strongly influence the entire recombination process. This phenomenon is also discussed and a simple technique for separation between bulk and interface recombination is proposed.

Keywords: OCVD, carrier lifetime, epitaxial layer characterization, interface recombination

1 INTRODUCTION

The open-circuit voltage decay (OCVD) technique was one of the earliest methods for carrier lifetime determination [1]. It is easy to implement, interpretation of experimental data is fairly straightforward and, moreover, very good correlation with real electrical parameters of devices is expected. In this method, a diode is forward biased and a steady-state carrier excess is established in the lightly doped region. Then the diode bias circuit is opened and subsequent excess carrier recombination is detected by monitoring the open circuit voltage. High-injection and low-injection lifetimes, $\tau_r(ll)$ and $\tau_r(hl)$, respectively, are then evaluated from two distinct regions of the voltage transient (V-t) respectively (Fig. 1).

In bipolar and unipolar technology, epitaxial (epi) layers are routinely used because they have a better surface and bulk quality than the Czochralski-grown silicon substrate. The quality of these layers could be evaluated with recombination or generation lifetime measurement in some way [2, 3]. However, there may arise some uncertainty in lifetime measurement due to the fact that epi layers are generally thinner than the minority carrier diffusion length, forasmuch as OCVD method (alike the most commonly used techniques such as surface photovoltage or photo-conductance decay) measures the recombination lifetime. Parameters obtained in this manner yield more information about the surface and epi layer/substrate interface than about the epi layer itself. Nevertheless, this difficulty can be overcome by growing an epi layer with counter doping type to the substrate, *ie*, by making of np^+ or pn^+ junction respectively and subsequent creation of high-low contact with diffusion or epitaxial growth with higher doping concentration (Fig. 2). This structure acts as an effective potential barrier for constraining the injected carriers within the lightly doped region, which can decrease with time only through electron-hole recombination. When the high-low contact is grown in one technological step with epi layer, *eg*, by extending the impurity flow or using the diffusion process, a high-quality n^+/n or p^+/p interface is expected, with a negligibly low recombination velocity, hence, the recombination lifetime is mostly influenced by the bulk of the lightly doped epi layer. Moreover, as will be mentioned in section 2, the width of lightly the doped region should be less than the ambipolar diffusion length, thereby this structure is suitable for thin epi layer characterization.

In this paper, we have analyzed n^+np^+ and p^+pn^+ structures, using both epi growth and diffusion for high-low contact preparation, respectively. The lifetime obtained from OCVD response using such structures has been discussed according to experimental as well as simulated I-V characteristics. Finally, a simple method for separation between interface and bulk recombination is proposed.

2 THEORETICAL BACKGROUND

In this section we consider the structure shown in Fig. 2a with a small short base. The recombination lifetime is determined by three main recombination mechanisms: Shockley-Read-Hall (SRH) or multiphonon recom-

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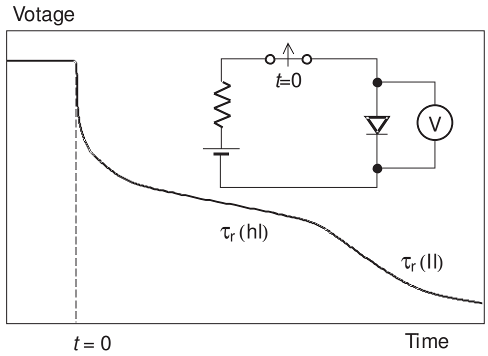

Fig. 1. OCVD measurement principle with voltage waveform and schematic (inset).

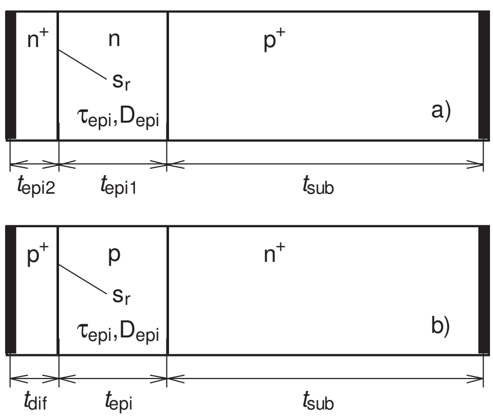

Fig. 2. Samples geometry for a.) n^+np^+ and b.) p^+pn^+ structures.

bination characterized by the lifetime $\tau_{\rm SRH}$, radiative recombination characterized by $\tau_{\rm rad}$, and Auger recombination $\tau_{\rm Auger}$ according to relationship [4]

$$\tau_r = \frac{1}{\tau_{\rm SRH}^{-1} + \tau_{\rm rad}^{-1} + \tau_{\rm Auger}^{-1}} \,. \tag{1}$$

Since Si is an indirect band-gap semiconductor, radiative recombination plays almost no role, moreover, the Auger effect can be neglected when the current density remains below $100\,{\rm A/cm^2}$ [5]. As shown below (see section 3), this condition will be fully satisfied. On the basis of this assumption, the recombination lifetime is controlled by SRH mechanism given by [4]

$$\tau_r \cong \tau_{\rm SRH} = \frac{\tau_p\big(n_0+n_1+\Delta p\big)+\tau_n\big(p_0+p_1+\Delta p\big)}{n_0+p_0+\Delta p} \,, \tag{2}$$

where only one dominant recombination centre is considered and n_1, p_1, τ_n and τ_p are defined as

$$n_1 = n_i \exp\Big(\frac{E_T-E_i}{kT}\Big), \tag{3a}$$

$$p_1 = n_i \exp\Big(-\frac{E_T-E_i}{kT}\Big), \tag{3b}$$

$$\tau_p = \frac{1}{\sigma_p \nu_{th} N_T} \,, \tag{4a}$$

$$\tau_n = \frac{1}{\sigma_n \nu_{th} N_T} \,. \tag{4b}$$

Here, n_0, p_0 and Δp are equilibrium or excess minority carrier densities in the base region, respectively, E_T is the trap energy level in the band-gap, E_i is the Fermi intrinsic energy level, $\sigma_{p,n}$ is the electron and hole capture cross section, respectively, v_{th} is the thermal velocity and N_T is the density of impurities, k is the Boltzmann constant and T is absolute temperature. Equation (2) simplifies for both low-level and high-level carrier injection. Under low-level condition, when the excess minority carrier density is low compared to the equilibrium majority carrier concentration $\Delta p \ll n_0$, recombination lifetime becomes

$$\tau_r(ll) \approx \tau_p\Big(1+\frac{n_1}{n_0}\Big) + \tau_n\frac{p_1}{n_0} \cong \tau_p \,, \tag{5}$$

where the second approximation is assumed, $n_1 \ll n_0$ and $p_1 \ll n_0$. Similarly, for high-level condition, when holds the inequality $\Delta p \gg n_0$, one gets expression

$$\tau_r(hl) \approx \tau_p + \tau_n \,. \tag{6}$$

2.1 High-level lifetime

Performing OCVD measurement under high-level condition, one should use a sufficiently large forward current during the initial pulse. Consider that the epi base width $t_{\rm epi1}$ is less than the ambipolar diffusion length $L_a = (2kT/q)\,[\mu_n\mu_p/(\mu_n+\mu_p)]\,\tau_r(hl)$, where $\mu_{n,p}$ is the electron or hole mobility, respectively and q is the electron charge. Concerning the charge neutrality condition, the total electron and hole concentrations given by

$$p_n = \Delta p + p_0 \,, \qquad n_n = \Delta n + n_0 \tag{7a, b}$$

are equal, moreover, it can be shown [6] that their distributions are uniform throughout the epi-base region, *ie*, $n_n(x) = p_n(x) = \text{const}$. When the forward current is abruptly terminated, injected carriers are constrained into the base region by the potential barriers across p^+n and n^+n junctions and subsequently recombination of excess carriers takes place, which is monitored as the open circuit voltage decay.

In general, the open voltage across the diode consists of three components: the voltage across the p^+n junction V_{j1}, the voltage across the n^+n high-low junction V_{j2} and the voltage across the n region V_b. The third component, Dember voltage vanishes because of uniform carrier distribution in epi layer. By evaluating and combining the first two voltages using Boltzmann's equation one can get

$$\frac{p_n n_n}{p_0^+ n_0^+} = \exp\Big[-\frac{q}{kT}(V_{bi1}-V_{bi2})\Big]\exp\Big[\frac{q}{kT}(V_{j1}+V_{j2})\Big], \tag{8}$$

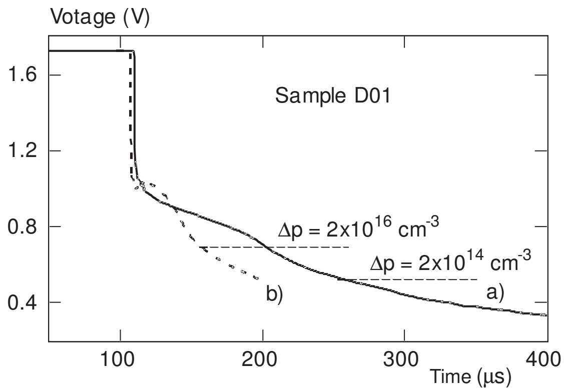

Fig. 3. OCVD response of the sample D01 a.) after edge etching and b.) before edge etching. Dash-dot lines denote injection levels of minority carriers.

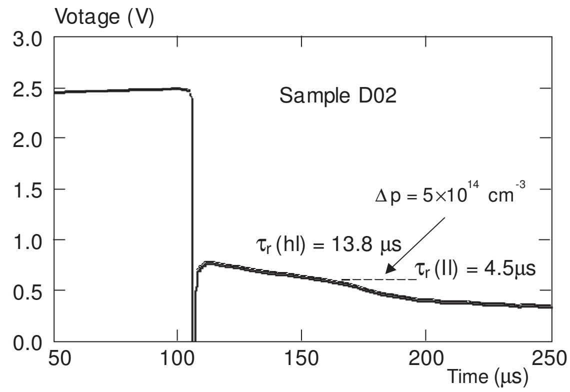

Fig. 4. OCVD response of the sample D02. Dash-dot line denotes injection level of minority carriers equal to base doping, *ie* transition from high to low-level injection.

where p_0^+ and n_0^+ denote equilibrium majority concentration in p^+ and n^+ regions, respectively, and V_{bi1}, V_{bi2} are built-in voltages of p^+n or n^+n junctions, respectively, which could be expressed as

$$\frac{p_0 n_0}{p_0^+ n_0^+} = \exp\Big[-\frac{q}{kT}(V_{bi1} - V_{bi2})\Big]. \tag{9}$$

Combining the equations (8) and (9) with taking into account that $p_0 n_0 = n_i^2$ and $p_n = n_n$ we get

$$\frac{p_n^2}{n_i^2} = \exp\Big(\frac{qV_t}{kT}\Big), \tag{10}$$

where $V_t = V_{j1} + V_{j2}$ is the total open circuit voltage for high-level condition.

The rate of recombination of injected carriers under high-level condition can be expressed as

$$-\frac{\mathrm{d}p_n}{\mathrm{d}t} = \frac{p_n}{\tau_r(hl)} \quad \text{or} \quad -\frac{\mathrm{d}(\ln p_n)}{\mathrm{d}t} = \frac{1}{\tau_r(hl)}\,. \tag{11a, b}$$

Hence, by differentiating equation (10) with respect to time, $\tau_r(hl)$ is given as

$$\tau_r(hl) = -\frac{2kT}{q}\Big(\frac{\mathrm{d}V}{\mathrm{d}t}\Big)^{-1}. \tag{12}$$

2.2 Low-level lifetime

At the low-level condition, the excess carrier concentrations $\Delta p(x)$ and $\Delta n(x)$ are once again uniform throughout epi layer because its width is smaller that the diffusion length, which in the present case is the minority carrier or hole diffusion length, *ie*, Equation voltages across junctions are now as follows

$$\frac{\Delta p + p_0}{p_0} = \exp\Big(\frac{qV_{j1}}{kT}\Big)\,, \tag{13a}$$

$$\frac{\Delta n + n_0}{n_0} = \exp\Big(\frac{qV_{j2}}{kT}\Big)\,. \tag{13b}$$

Under low-level condition, inequalities $\Delta p \gg p_0$ and $\Delta n \ll n_0$ hold. Consequently, if one applies these inequalities to the above equations, it is clear that $V_{j1} \gg V_{j2}$, thus the total open circuit voltage is equal only to the voltage across p^+n, $V_t = V_{j1}$. The excess carrier concentration is then given by

$$\Delta p = p_0\Big[\exp\Big(\frac{qV_t}{kT}\Big) - 1\Big]. \tag{14}$$

Considering an idealized situation, where the carrier trapping and surface effect can be neglected, the decay of excess carriers is governed as

$$-\frac{\mathrm{d}\Delta p}{\mathrm{d}t} = \frac{\Delta p}{\tau_r(ll)}\,. \tag{15}$$

By combining equations (14) and (15) and assuming the total voltage to be much larger than kT/q gives

$$\tau_r(ll) = -\frac{kT}{q}\Big(\frac{\mathrm{d}V}{\mathrm{d}t}\Big)^{-1}. \tag{16}$$

2.3 Surface and interface recombination

Recombination process during OCVD transient in samples shown in Fig. 2 is affected not only by bulk recombination but it is given by lateral surface recombination and interface recombination at the high/low contact. Unlike in usually used structures [3], in our configuration only one interface contributes to entire recombination on the assumption that carrier trapping is neglected. Although the interface recombination velocity s_r of a high/low junction tends to be low, it could have a significant influence on the measured lifetime especially when epi layer lifetime τ_{epi} is of the order of several hundreds of μs, which is really the case in today's state of technology. Therefore, it is convenient to define the effective lifetime τ_{reff}, which can be written as [7]

$$\frac{1}{\tau_{\mathrm{reff}}} = \frac{1}{\tau_{\mathrm{epi}}} + \frac{1}{\tau_s} = \frac{1}{\tau_{\mathrm{epi}}} + D_{\mathrm{epi}}\beta^2\,, \tag{17}$$

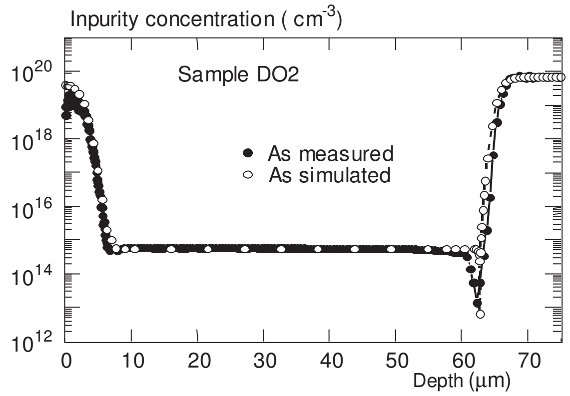

Fig. 5. Experimental (spreading resistance profiling) and simulated impurity depth profile of the sample D02.

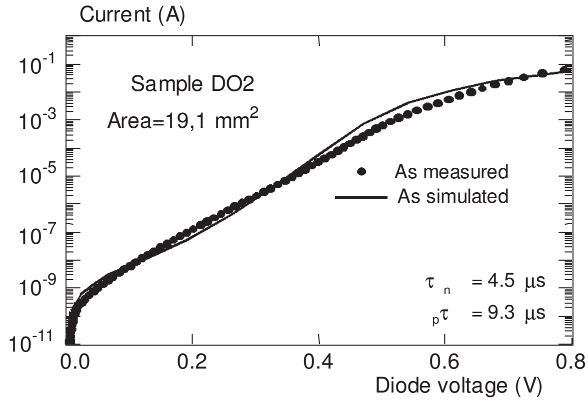

Fig. 6. As measured and simulated I-V characteristic of the sample D02. For simulation, τ_n and τ_p obtained from OCVD measurement was used with assumption that energy of dominant trap is located at mid-gap $E_T = E_i$.

where τ_s is the surface/interface lifetime, $D_{\rm epi}$, $t_{\rm epi}$ is the diffusion coefficient and thickness of epi layer, respectively, and the parameter β is determined from the implicit equation

$$\cot(\beta t_{\rm epi}) = \frac{\beta D_{\rm epi}}{s_r}\,. \tag{18}$$

Separation of surface recombination component is quite difficult. Nevertheless, we will discuss this issue in more detail in section 3 on the basis of correlation between the measured data and those calculated according to the above equations.

The influence of lateral surface recombination is illustrated in Fig. 3 on curve b (dashed line). Such a transient was recorded immediately after sample separation by wafer cleaving. However, this effect could be sufficiently suppressed by performing edge etching, moreover, for the large diameter of the diode used in collecting the experimental data, perimeter recombination can be neglected, when the effective lifetime remains below 10^{-3} s [8].

3 EXPERIMENT

The circuit arrangement used for OCVD measurement comprised a Lifetime Test Unit OCD-2B containing a power supply and a fast transistor switch. The open circuit voltage decay was monitored by Tektronix TDS3000B digital oscilloscope and I-V characteristics of the diodes under study were recorded using Keithley 237 Source Meter. For simulation, commercial software ISE TCAD 9.0 was used.

3.1 Sample preparation

To cover both p-type as well as n-type epi layers characterization, two series of samples were used, denoted as D01 and D02. Sample D01 was prepared on a ⟨111⟩-oriented p-type boron doped 525 μm thick substrate with concentration 3.24×10^{18}–$1.34\times10^{19}\,{\rm cm}^{-3}$. Two n-type epi layers were grown step by step with phosphorous doping. The first one with a thickness of 50 μm has concentration $2\times10^{14}\,{\rm cm}^{-3}$ and at the second one with thickness of $\approx 5\,\mu$m, phosphorous concentration was increased by two orders. The resulting base thickness was approximately 55 μm.

Sample D02 was prepared on a ⟨111⟩-oriented n-type phosphorous doped 375 μm thick substrate with concentration higher than $6.6\times10^{18}\,{\rm cm}^{-3}$. P-type epi layer was grown with boron concentration of $5\times10^{14}\,{\rm cm}^{-3}$ but, unlike D01, high/low junction was created by boron diffusion. The resulting base width of sample D02 was similar to those of D01. AlSiCu contacts were prepared by ions sputtering (a thickness 1.5 μm) and after that, wafers were cutting to periodical hexagons (with area 19.1 mm^2). Prior to plasma etching of samples edges, they were partially packaged.

4 RESULTS AND DISCUSSION

Figure 3 shows a typical OCVD response of the sample D01 (curve a drawn by solid line) and, as mentioned above, voltage transient influenced by high lateral recombination surface velocity (curve b) is also reported. It is clearly demonstrated that lateral recombination is effectively suppressed because it affects both the transient shortening and its shape but the shape of the curve is quite different, thereafter we suppose lateral contribution to be insignificant.

In Fig. 3a, two regions could be distinguished which represent typical OCVD for high-level (herein 140–180 μs) and subsequent low-level (190–215 μs) lifetime measurement. However, from the conversion of the voltage curve

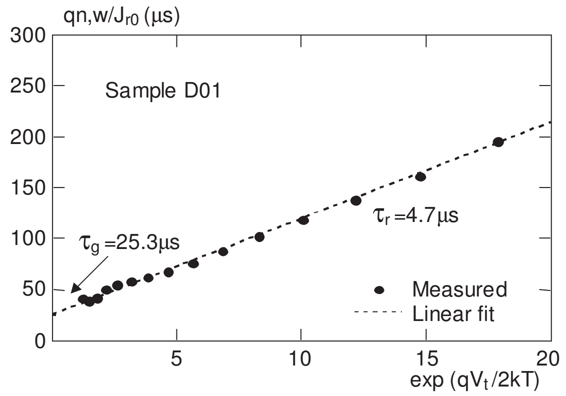

Fig. 7. Extraction of recombination and generation lifetime from I-V and C-V experimental data according to ref. [10].

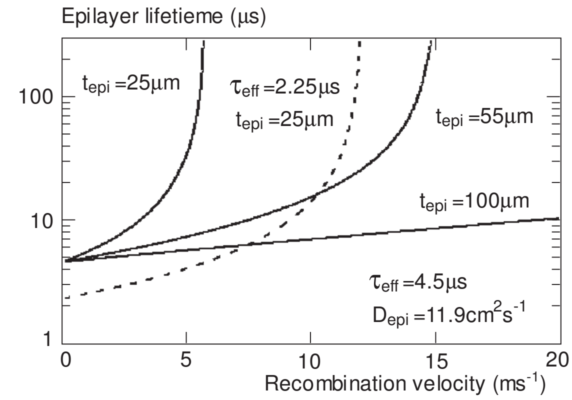

Fig. 8. Epitaxial layer lifetime $\tau_{\rm epi}$ versus recombination velocity s_r as a function of layer thickness for given effective lifetime. Solid line is solved for $\tau_{\rm eff} = 4.5\,\mu$s and dash line for $\tau_{\rm eff} = 2.25\,\mu$s.

into the excess carrier density transient by equation

$$[\Delta p + p_0]\,[\Delta p + n_0] = n_i^2 \exp\Big(\frac{qV_t}{kT}\Big)\,, \qquad (20)$$

(concentrations are labelled by horizontal dash-dot line in Fig. 3) one can see that at $t = 193\,\mu$s minority excess carriers decrease only below the majority concentration in n$^+$ emitter and they decrease under base majority concentration as far as $t = 260\,\mu$s. Hence, at the earlier part of the voltage decay, the diode behaves as an Rnp$^+$ structure (R denotes an ohmic contact with an infinite recombination rate). The effective lifetime obtained from this transient could lead to misinterpretation, nevertheless, providing appropriate analysis, correct value of the lifetime could be obtained [9].

A typical OCVD response of the structure D02 is shown in Fig. 4. Unlike sample D01, high- low junction of the diode D02 was prepared by diffusion with p$^+$ concentration of three orders above the epi p-base doping, which is accomplish by the depth profile obtained from spreading resistance profiling measurements as well as simulation of technological process (Fig. 5). Using eqn. (20) again, the excess carrier concentration was determined and compared with base doping labelled by the dash-dot line in Fig. 4. Here, the value of injected carrier correlates well with the transition between the high and low-level injection. Thereafter, proper lifetimes could be determined. From the fitting of distinct regions at the curve it was extracted as $\tau_r(hl) = 13.8\,\mu$s and $\tau_r(ll) = 4.5\,\mu$s and according to equations (5) and (6) one can obtain carrier lifetimes $\tau_n = 4.5\,\mu$s and $\tau_p = 9.3\,\mu$s.

In order to verify the obtained value of recombination lifetimes we realized the procedure for τ_r and τ_g (generation lifetime) determination proposed by Poyai *et al* [10] based on extracting the recombination current from the forward current-voltage (I-V) characteristic of the diode using both I-V and C-V measurements. It should be noted that since our diodes have a sufficiently large area, we did not separate the perimeter and bulk current densities. An experimental I-V characteristic of diode D02 is shown in Fig. 6, from here we derived the diffusion current density as $J_{d0} = 80$ pA. The diode current density can be written as

$$J = \Big[J_{d0} + \frac{qn_iw}{2\tau_i \exp(qV_i/2kT) + \tau_g}\Big]\Big[\exp\Big(\frac{qV_t}{kT}\Big) - 1\Big], \quad (21)$$

where $w(= \varepsilon_{\rm Si}/C_j$, $\varepsilon_{\rm Si}$ is the silicon permittivity and C_j is the junction capacitance [10]) is the depletion width. By plotting $\big(qn_iw/J_{r0}\big)$ versus $\exp\big(qV_t/2kT\big)$, as shown in Fig. 7, τ_r and τ_g can be obtained from the slope and intercept of the experimental data, respectively. The recombination lifetime of $4.7\,\mu$s was found. It is obvious that the lifetime obtained by this procedure corresponds to low-level carrier injection, which is in excellent agreement with that acquired from the OCVD technique ($4.5\,\mu$s).

Moreover, we realized appropriate simulation of the I-V characteristic, where the simulated concentration profile from Fig. 5 and measured lifetimes were used as input parameters. These lifetimes were considered only in the base region while in highly doped regions the standard doping dependence model was employed [11]. The recombination current was solved by SRH model with a single dominant level assuming that the energy of trap is located at mid-gap $E_T = E_i$. The simulated I-V characteristic is shown in Fig. 6 (drown by solid line) and one can see good matching between simulated and experimental data. Note that we did not make any additional fitting procedures. Some discrepancies could arise from the low accuracy of spreading resistance profiling measurement and/or from low-level lifetime extraction, which is in general not as ease to evaluate as the high-level one.

How can be evaluated $\tau_{\rm epi}$? Figure 8 shows correlation between $\tau_{\rm epi}$ and s_r for a given low-level effective lifetime $\tau_{\rm eff} = 4.5\,\mu$s as a function of epi layer thickness calculated according to eqns. (17) and (18). It demonstrates that with decreasing the thickness of the epi layer the influence of interface recombination becomes more significant. Now, consider a structure with $t_{\rm epi} = 25\,\mu$m and approximately equal epi layer parameters, *ie*, $\tau_{\rm epi}(25\,\mu{\rm m}) \cong \tau_{\rm epi}(55\,\mu{\rm m})$ (the same process condition). One can expect the lower value of τ_{eff}, according to structure with $55\,\mu$m thick epi layer. As an example, we assume $\tau_{\text{eff}} = 2.25\,\mu$s. This calculation is drawn in Fig. 8 by the dashed line. Since the minority excess carrier concentration is uniform trough the epi base ($t_{\text{epi}} \ll L_n$), s_r is equal for both structures due to the same minority carrier concentrations at the p^+/p interface. Only β changes with τ_{eff} decreasing in the right side of eqn. (17). Consequently, solution is represented by intersection of the solid ($t_{\text{epi}} = 55\,\mu$m) and dashed lines ($t_{\text{epi}} = 25\,\mu$m) in Fig. 8, resulting in $\tau_{\text{epi}} = 16.3\,\mu$s and $s_r = 10.25$ m/s. If one uses more than two layer thicknesses, reliability of proposed technique can be estimated, whereas all three τ_{epi} versus s_r plots should meet in one point.

Although, it is only consideration, manufacturing of structures with various t_{epi} is under progress.

5 CONCLUSION

We have explored the applicability of the open circuit voltage decay for epitaxial layer characterization using a specially designed diode structure. It was shoved experimentally that a diode structure with sufficiently high concentration of high/low emitter OCVD technique could be used for epi layer characterization. The OCVD lifetime is in excellent agreement with that obtained from other methods as well as with simulated data. A simple procedure for separation between interface and bulk recombination was also proposed, however, its reliability has to be examined by measuring on diode structures with different base widths.

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