Silicon Epitaxial Layer Recombination and Generation Lifetime Characterization

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***Abstract*—We have made recombination and generation lifetime measurements on silicon p-epitaxial layers on p^+ and on p-substrates. The recombination lifetimes are dominated by surface/interface recombination for layers only a few microns thick. By coupling measurements of p/p with those of p/p^+ samples, it is possible to extract the epi-layer lifetime. For p/p^+ samples, recombination lifetimes are poorly suited to characterize epi-layers. Generation lifetime measurements are eminently suitable for epi-layer characterization, since carrier generation occurs in the space-charge region confined to the epitaxial layer, and when coupled with corona charge/Kelvin probe, allow contact-less measurements.**

***Index Terms*—Carrier lifetimes, epitaxial layers, MOS capacitors, semiconductor device measurements, semiconductor materials, semiconductors, silicon.**

I. INTRODUCTION

BIPOLAR junction transistor, and some MOSFET circuits, use epitaxial layers. The epitaxial film thickness and doping density are routinely evaluated by optical and capacitance-voltage measurements, respectively. The "defect" quality of the layers can be evaluated with techniques that determine the carrier lifetime in some way. For example, one can use photoluminescence [1], [2] or lifetime measurements. The most common carrier lifetime characterization techniques measure the *recombination lifetime* or the *minority carrier diffusion length*. Such parameters typically yield more information about the surface and the epi/substrate interface than about the epi-layer itself, because the layers are typically much thinner than the minority-carrier diffusion length. Techniques that determine the *generation lifetime* are more suitable, because the carrier generation volume is confined to the epi-layer.

The *recombination* lifetime τ_r, or the minority-carrier diffusion length L_n, of bulk semiconductor samples is routinely measured by microwave-photoconductance decay [3], [4] surface photovoltage [5], electrolytical metal tracer (ELYMAT) [6], and other techniques [7]. All of these measurements determine effective values, more or less influenced by surface/interface recombination, accentuated for thinner samples and hence, are poorly suited for epitaxial layer characterization, as we will show. The *generation* lifetime, typically determined with pulsed MOS capacitors or pulsed corona charge, is a localized characterization technique that measures carrier generation in the space-charge region that is confined to the epitaxial layer. We report recombination and generation lifetime measurements on epitaxial layers of various thicknesses. Epitaxial layer characterization with frequency-dependent, surface photovoltage measurements has been described previously [8].

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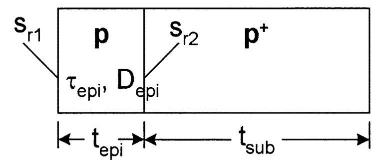

Fig. 1. Sample geometry with layer thickness t_{epi}, surface recombination velocity s_{r1}, interface recombination velocity s_{r2}, layer lifetime τ_{epi}, diffusion coefficient D_{epi}, and substrate thickness t_{sub}.

II. THEORY

A. Recombination Lifetime

Consider the sample in Fig. 1, consisting of a p-epitaxial layer on a p^+-substrate. The layer is characterized by surface *recombination* velocity s_{r1} and interface *recombination* velocity s_{r2}, layer recombination lifetime τ_{epi}, diffusion coefficient D_{epi}, and thickness t_{epi}. The effective recombination lifetime τ_{reff} can be written as [9]

$$\frac{1}{\tau_{reff}} = \frac{1}{\tau_{epi}} + \frac{1}{\tau_S} = \frac{1}{\tau_{epi}} + D_{epi}\beta^2 \quad (1)$$

where τ_S is the surface/interface lifetime. The parameter β is determined from the implicit equation

$$\cot(\beta t_{epi}) = \frac{\beta^2 D_{epi}^2 - s_{r1}s_{r2}}{\beta D_{epi}(s_{r1}+s_{r2})} \quad (2)$$

τ_{reff}, determined from (1) and (2), is plotted in Fig. 2 with $s_{r1} = s_{r2} = s_r$.

It is quite obvious that unless the sample is extremely thick, the effective recombination lifetime is substantially lower than the layer lifetime τ_{epi}, unless surface recombination is negligibly low. Even for a modest surface recombination velocity of 100 cm/s, the effective lifetime for epitaxial layers with typical

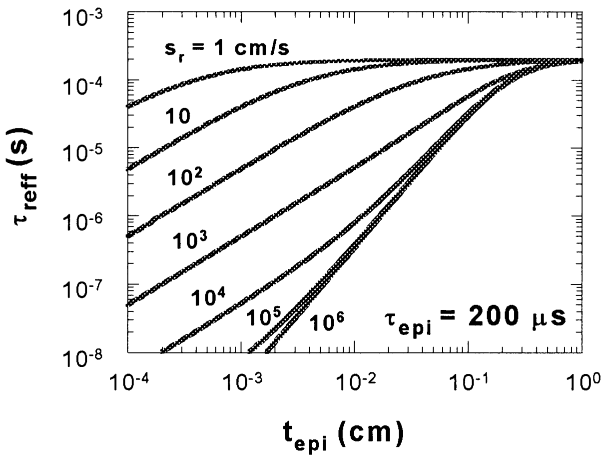

Fig. 2. Effective recombination lifetime versus layer thickness for $\tau_{epi} = 200\ \mu$s as a function of $s_{r1} = s_{r2} = s_r$.

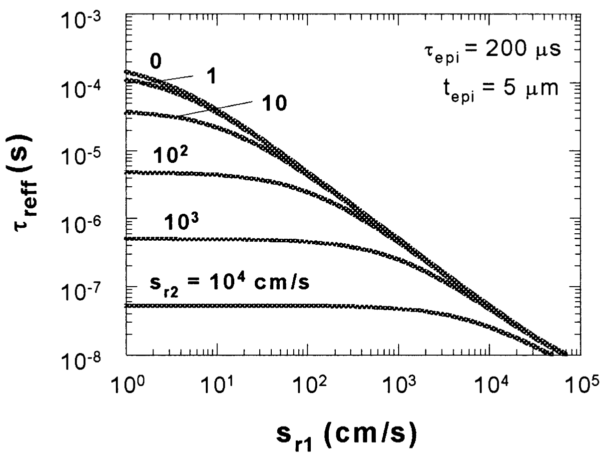

Fig. 3. Effective recombination lifetime versus s_{r1} as a function of s_{r2} for a 5-μm-thick layer with $\tau_{epi} = 200\ \mu$s.

thicknesses of several microns, is about 100 times lower than τ_{epi}. We chose $\tau_{epi} = 200\ \mu$s in these calculations, because the lifetimes in today's epitaxial layers are on the order of several hundred μs. The result of varying s_{r1} and s_{r2} independently of each other is illustrated in Fig. 3, again showing that both recombination velocities need to be very low to measure lifetimes that are reasonably close to τ_{epi}.

How can surface recombination be controlled, especially to obtain low values? The surface recombination velocity at the front surface s_{r1}, is difficult to predict, because it depends on the condition of the front surface, i.e., flat band, accumulation, depletion, or inversion. The state of the surface can, of course be controlled for a MOS device by the gate voltage. It can also be controlled for an oxidized wafer with corona charge. At flat band, both minority electrons and majority holes can reach the surface to recombine there, leading to a high s_{r1}. In accumulation, some minority electrons are repelled by the electric field and most of the surface states are occupied by holes, making surface recombination inefficient with a concomitant low s_{r1}. In depletion and weak inversion, electrons drift to the surface and the energy barrier for holes is sufficiently low for effective surface recombination leading to high s_{r1}. In strong inversion, the hole barrier increases and most of the surface states are occupied by electrons, leading to low s_{r1}. Various approaches have been used to reduce s_{r1}, e.g., oxidation, dilute hydrofluoric acid (HF) [10], iodine/ethanol [11], iodine or bromine/methanol [12], H_2SO_4/H_2O_2, $HCl/H_2O_2/H_2O$, $NH_4OH/H_2O_2/H_2O$, HNO_3, quinhydrone/methanol [13], corona charge [14], [15] external electric field [16], and ELYMAT bias voltage [17].

The interface recombination velocity of a low/high p/p$^+$ junction tends to be low, since such a junction is a minority carrier reflector. Its interface recombination velocity is given by [18], [19]

$$s_{r2} = \frac{N_{epi}}{N_{sub}}\frac{D_{sub}}{L_{sub}}\exp\left[(\Delta E_{G,\,sub} - \Delta E_{G,\,epi})/\,kT\right] \cdot \frac{(s_b L_{sub}/D_{sub}) + \tanh(t_{sub}/L_{sub})}{1 + (s_b L_{sub}/D_{sub})\tanh(t_{sub}/L_{sub})} \quad (3)$$

where N_{epi} and N_{sub} are the doping densities, D_{sub} and L_{sub} the substrate diffusion constant and minority carrier diffusion length, $\Delta E_{G,\,epi}$ and $\Delta E_{G,\,sub}$ are the band gap narrowing of the epi-layer and substrate, respectively, s_b is the surface recombination velocity at the substrate surface, and t_{sub} is the substrate thickness. Note that s_{r2} in (3) does not include the recombination effect in the low/high junction transition region. Band-gap narrowing is described by [20]

$$\Delta E_G = 0.231\left[\left(\frac{10^{20}}{N_A}\right)^{0.75} + 1\right]^{-2/3} \quad (4)$$

where N_A has the units of cm^{-3}. The substrate diffusion constant and lifetime are [20]

$$D_{sub} = \frac{35}{1 + (N_{sub}/10^{17})^{0.6}} + 1.8$$

$$\tau_{sub} = \left(1.2\times10^{-31}N_{sub}^2 + (1 + N_{sub}/7\times10^{15})/\tau_o\right)^{-1} \quad (5)$$

where N_{sub} is in cm^{-3} and τ_0 is in seconds. The diffusion length is given by

$$L_{sub} = \sqrt{D_{sub}\tau_{sub}}. \quad (6)$$

Fig. 4 shows s_{r2} according to (3) for $N_{epi} = 1.5 \times 10^{15}$ cm^{-3}, $t_{sub} = 600\ \mu$m, $s_b = 10^6$ cm/s, and $\tau_o = 200\ \mu$s. Although the N_{sub} in the denominator suggests an s_{r2} reduction, it is the band-gap narrowing that causes s_{r2} to increase. For substrate doping densities in the range of 5×10^{18} to 5×10^{19} cm^{-3}, s_{r2} varies from about 10 to 70 cm/s, and according to Fig. 3, degrades τ_{reff} significantly for low s_{r1}.

B. Generation Lifetime

A more appropriate technique for *localized* lifetime characterization is a measurement of the effective *generation* lifetime. Bulk and surface generation, of course, also determine the generation rate, but the room-temperature generation volume is well-defined by the space-charge region (scr) width and device

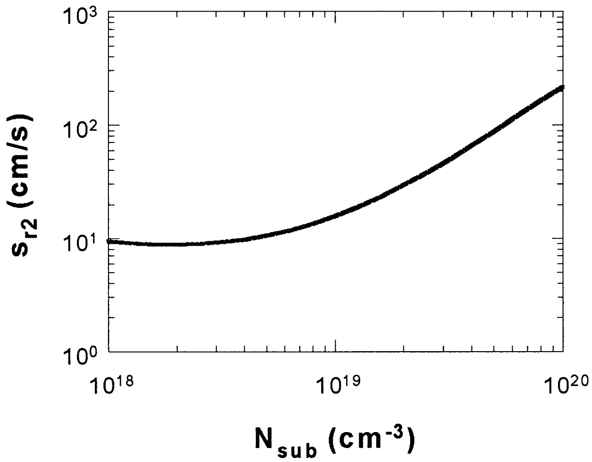

Fig. 4. Effective interface recombination velocity versus substrate doping density. $N_{epi} = 1.5 \times 10^{15}$ cm^{-3}, $t_{sub} = 600$ μm, $s_b = 10^6$ cm/s, and $\tau_o = 200$ μs.

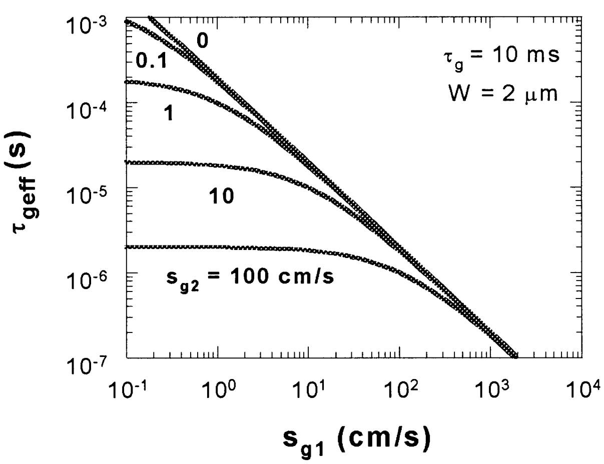

Fig. 5. Effective generation lifetime versus s_{g1} as a function of s_{g2} for a 2-μm space-charge region width with $\tau_g = 10$ ms, a typical value for high-quality silicon.

area, both under operator control. The effective generation lifetime is given by [21]

$$\tau_{geff} = \frac{\tau_g}{1 + \tau_g(s_{g1} + s_{g2})/W} \quad (7)$$

where W is the scr width, τ_g the generation lifetime, and s_{g1} and s_{g2} the surface *generation* velocities at the top and bottom film surfaces, respectively. The effects of bulk and surface generation on the effective generation lifetime are shown in Fig. 5. Similar to Fig. 3, where surface recombination dominates the effective recombination lifetime, Fig. 5 shows that surface generation dominates the effective generation lifetime unless s_{g1} and s_{g2} are very low. In contrast to surface recombination velocities, however, which are difficult to reduce below 10 cm/s, surface generation velocities on the order of 1 cm/s are routinely achieved for oxidized/annealed SiO_2/Si interfaces used in these experiments.

III. Previous Publications

The upper epitaxial surface s_{r1} can be controlled with appropriate chemical passivation or corona charge. What are experimental values for s_{r2} of low/high interfaces? Takahashi and Maekawa characterized the n/n$^+$ interface by selectively etching the substrate and measuring the Schottky diode leakage current [22]. They found the interface recombination to be 10.6 cm/s at low injection level and 21.8 cm/s at increased injection. This compares to $s_{r2} = 400$ and 14 cm/s determined by others [23], [24].

Ogita used a 40-mW microwave signal at $f = 100$ GHz and 1-ns wide N_2 and laser pulses with a penetration depth of 20 nm [25]. The resistivity of the epi-layers varied from 5 to 50 Ω-cm and that of the substrates from 0.008 to 0.05 Ω-cm. He found the effective lifetimes of p/p$^+$ and n/n$^+$ samples to be 0.76 and 0.2 μs, respectively. These lifetimes increased to 5 and 1.5 μs when the epi surface was corona charged, reducing the surface recombination velocity. Through fitting of experiment to theory, he determined s_{r2} to be less than about 350 cm/s.

Hara *et al.* used n/n samples with $t_{epi} = 30$ μm, $\rho_{epi} = 25$ Ω-cm and $t_{sub} = 600$ μm and $\rho_{sub} = 25$ Ω-cm [26]. This sample had no minority carrier barrier at the epi-substrate interface. Photoconductance decay measurements gave $\tau_{eff} = 8$ μs initially. This value increased to 24 μs when the epi surface was passivated with an iodine/methanol solution. It increased further to 120 μs when the substrate surface was also passivated. After etching the epi-layer, the substrate yielded $\tau_{reff} = 153$ μs, allowing the epi lifetime to be calculated as 450 μs. The optical excitation was provided by light with $\lambda = 902$ nm and a penetration depth of 25 μm.

Takahashi and Maekawa used n/n samples with $t_{epi} = 20$ μm, $\rho_{epi} = 10$ Ω-cm, and $t_{sub} = 720$ μm and $\rho_{sub} = 41$ Ω-cm [27]. By measuring the lifetime of the epi/substrate sample, and then etching the epi-layer, they determined $\tau_{sub} = 2.15$ ms and $\tau_{epi} = 250$ μs. They assumed the surface recombination velocity of the iodine/methanol-passivated surface to be 13.6 cm/s. Makino *et al.* formed n/n$^+$ and p/p$^+$ low/high junctions by ion implantation [28]. By fitting photoconductance decay curves to theory, they extracted the interface recombination velocities and found s_{r2} for n/n$^+$ interfaces to vary from ~1000 cm/s for a 10^{12} cm^{-2} implant dose to ~10 cm/s for 10^{15} cm^{-2}. For p/p$^+$ interfaces, the values were ~8000 to 100 cm/s.

Although there is a wide variation of reported s_r for low/high junctions, a reasonable estimate for such junctions for fairly heavily doped "high" regions is in the range of 10-100 cm/s, also obtained in our calculation in Fig. 4.

IV. Experimental

To determine the epitaxial layer lifetimes, we made a variety of recombination and generation lifetime measurements. The p-type epitaxial layers on p-type substrates were grown at Nippon Steel and consisted of the layers in Table I. Table I and Fig. 6 also contain the various lifetimes, to be discussed below. We used microwave PCD measurements at Semilab, corona charge-based recombination and generation lifetime measurements at Agere, and surface photovoltage and pulsed MOS capacitor generation lifetime measurements at Arizona State University. All wafers were oxidized to 10 nm to passivate the surface and to reduce the surface recombination velocity s_{r1}.

TABLE I
EPI-LAYER RESISTIVITY AND THICKNESS, SUBSTRATE RESISTIVITY, AND EFFECTIVE LIFETIMES

ρ_{epi} (ohm-cm)	t_{epi} (μm)	ρ_{sub} (ohm-cm)	τ_{reff} (PCD) (μs)	τ_{reff} (Corona) (μs)	τ_{reff} (SPV) (μs)	τ_{geff} (Corona) (μs)	τ_{geff} (MOS-C) (μs)
8-12	1	0.006	2	90	0.0084	2500	1600
8-12	2	0.006	1.8	146	0.011	3500	1600
8-12	3	0.006	2.8	188	0.013	2600	1600
8-12	5	0.006	5.7	151	0.016	2100	1600
8-12	10	0.006	11.2	161	0.043	2100	1800
8-12	5	0.013	3.4	273			
8-12	5	10	120	675	70		

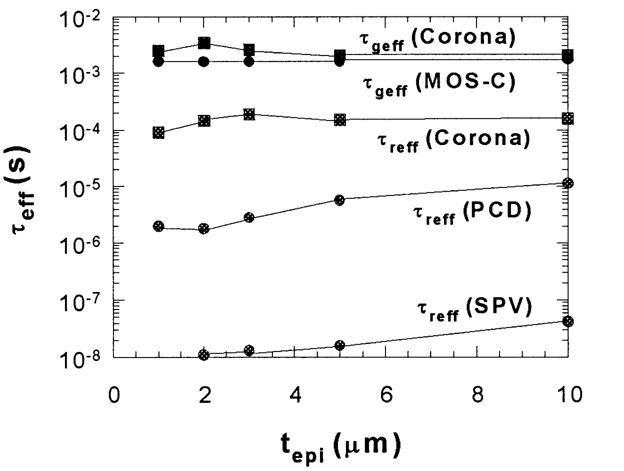

Fig. 6. Effective recombination and generation lifetimes versus epitaxial layer thickness.

A. Microwave-PCD Measurements

The microwave-photoconductance decay (μ-PCD) effective recombination lifetime measurement is illustrated in Fig. 7(a). High-resolution minority carrier lifetime measurements were made at Semilab with the standard μ-PCD and the one-point Epi-PCD technique. The excitation light was a 904 nm wavelength semiconductor laser with a penetration depth of about 30 μm. The lifetime map measurements (not shown here) were carried out with 2 mm lateral resolution after an automatic parameter setting procedure. The one-point lifetime results are shown in Table I and in Fig. 8. Lifetime maps for the 10 Ω-cm substrate gave values similar to the one-point data. The μ-PCD data are given in Fig. 8. Using $s_{r1} = 20$ cm/s and $s_{r2} = 70$ cm/s, we obtain good agreement between measured data and theory. From these data we estimate the epi lifetime to be about 160 μs.

To contain the microwave signal predominantly in the epi-layer, it should penetrate as little as possible into the substrate, requiring high frequencies. Electromagnetic wave penetration into a semiconductor is given by the skin depth

$$\delta = \sqrt{\rho/\pi f \mu_o} = 5.03 \times 10^3 \sqrt{\rho/f} \text{ cm} \quad (8)$$

where ρ is the resistivity (Ω-cm), f the microwave signal frequency (Hz), and μ_o the permeability of free space. For example, for $\rho = 0.001$ Ω-cm, $\delta = 5$ μm for $f = 100$ GHz and 16 μm for $f = 10$ GHz.

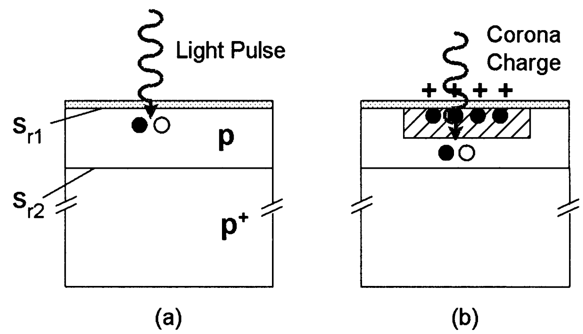

Fig. 7. (a) Photoconductance decay and (b) corona charge recombination lifetime measurements.

B. Corona Recombination Lifetime Measurements

The corona effective recombination lifetime measurement is illustrated in Fig. 7(b). The measurements were made with the Quantox XP system. Positive corona charge deposited onto the oxidized wafer induces a zero-biased np junction. A light pulse, of wavelength 900 nm, creates electron-hole pairs (ehp), forward biasing this field-induced junction. Upon termination of the light pulse, the ehp recombine leading to a time-dependent surface voltage, detected with a Kelvin probe. This measurement is similar to the open-circuit voltage decay technique [29]. The light pulse intensity is such that the lifetime measurements are made under high-level injection conditions.

The lifetime results are shown in Table I and in Fig. 8. Also shown are theoretical curves calculated with (1) and (2). Using (1) and (2), we obtain reasonable agreement between theory and experiment only for extremely low surface recombination velocities. It may be reasonable to use such low s_{r1}, since the corona charge-induced inversion layer shields the epi-layer surface. However, the low s_{r2} is unrealistic, especially for high-level injection, where the minority carrier barrier at the low/high junction is reduced [30].

C. Surface Photovoltage Measurements

The surface photovoltage measurements were made at ASU with an SDI CMS IIIA system using the 0.8–1.1 μm wavelength range. It is well known that minority carrier diffusion length measurements of epitaxial layers yield more or less the epitaxial layer thickness [8], [31], [32]. Our data are shown in Fig. 9. Although the linear relationship is not strictly observed, neverthe-

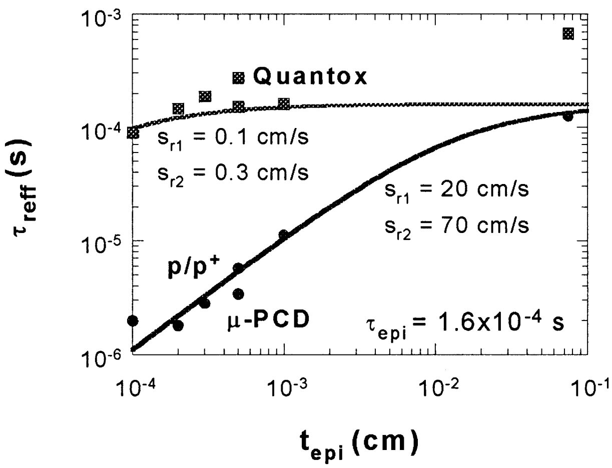

Fig. 8. Effective recombination lifetimes versus epi-layer thickness.

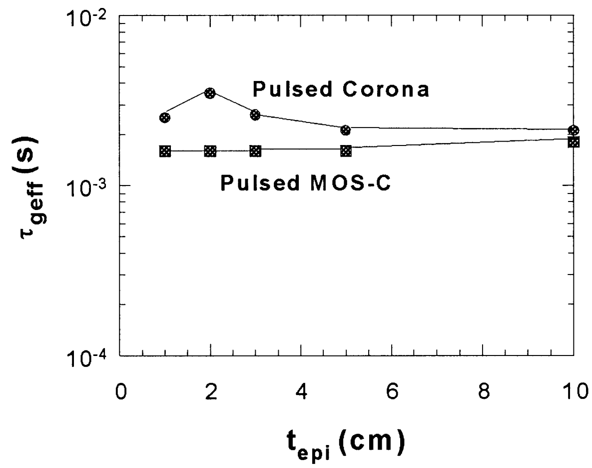

Fig. 10. Effective generation lifetimes versus epitaxial layer thickness for both Quantox and pulsed MOS-C measurements.

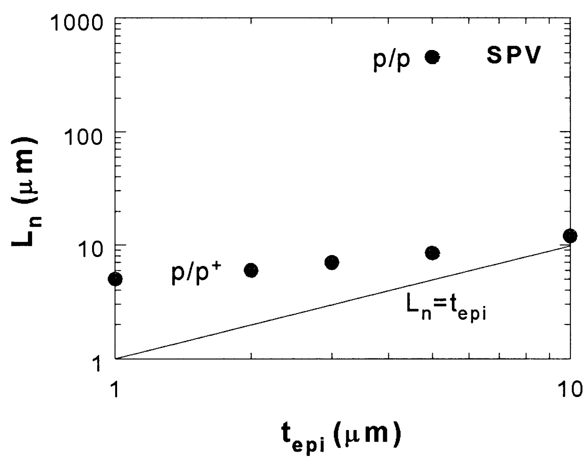

Fig. 9. Minority carrier diffusion length versus epitaxial layer thickness.

less we see the correct trend, i.e., the measured diffusion length is approximately equal to the epitaxial layer thickness. Note, that the measured diffusion length of the 10 Ω-cm on 10 Ω-cm sample is much higher at 450 μm, as expected. It is reasonable to assume that the actual diffusion lengths in all epitaxial layers are approximately the same. The fact that they are measured so differently is a reflection of the geometry, not the "defect" properties of the layers. These results clearly show that diffusion length measurements are not suitable for epi-layer characterization, as also shown in Table I, where the SPV recombination lifetimes ($\tau_{SPV} = L_n^2/D_n$) are significantly lower than any of the other lifetimes.

D. Pulsed Corona Generation Lifetime Measurements

The effective generation lifetime was measured by pulse depositing a corona charge on the oxidized sample surface with the sample in the dark. The charge pulse drives the device into depletion and it subsequently relaxes through thermal ehp generation. The resulting voltage transient is measured with a Kelvin probe [33]. The effective generation lifetimes so determined are shown in Fig. 10. As expected for high-quality layers, the lifetimes lie in the 2–3 ms range.

E. Pulsed MOS Capacitor Measurements

The effective generation lifetime measurements are made by pulse biasing an MOS capacitor (MOS-C) and measuring the resulting capacitance transient [34]. The MOS-C was fabricated by evaporated aluminum gates followed by forming gas anneal at 400 °C/30 min. For both generation lifetime measurements, the lifetime is measured in the pulse-induced space-charge region width, dependent on the applied voltage. Since the scr width is localized within the epi-layer, both generation lifetime techniques are well suited for epi-layer characterization, since the scr width can easily be controlled to one or a few microns. The measured lifetimes are shown in Fig. 10. There is reasonable agreement between the two methods, with effective generation lifetimes in the 1.5 to 3 ms range. These values are typical of high-quality Si. Furthermore, typical generation lifetimes are on the order 10 times the recombination lifetimes [35]. Comparing the true layer lifetime for the sample on the high-resistivity substrate of 125 μs with the generation lifetime of 1.5–3 ms, yields a ratio of 10–20, as expected.

V. Summary

We find the only unambiguous method to characterize the "defect" properties of epitaxial layers to be generation lifetime measurements, because the electron-hole pair generation volume is confined to the epitaxial layer by the space-charge region, and surface effects play a secondary role. Both pulsed MOS capacitor and pulsed corona charge give similar values. In contrast, recombination-lifetime measurements by photoconductance decay, surface photovoltage, or corona charge are strongly influenced or dominated by surface/interface recombination and do not yield reliable lifetimes.

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