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Minority Charge Carrier Lifetime for Evaluating 4H-SiC Epitaxial Growth by Microwave Detected Photoconductivity Decay

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Abstract. The quality of the epitaxial layer plays an important role in the performance of modern power electronic devices. Minority carrier lifetime is known to be sensitive to defects like dislocations, stacking faults, and points defects. Therefore, in this work lifetime measurements by microwave detected photoconductivity decay are used to evaluate the quality of the epitaxial layer on various 4H-SiC substrates from different vendors. The stability of the measurement technique is shown by a daily release measurement. This allows for a reliable analysis of almost 300 typical 1,200 V epilayer stacks. It has been shown that the effective lifetime of these samples can be separated into two different ranges. The lifetime values of about 120 ns fit to theoretical calculations. The cause for the increased lifetime of about 250 ns in the second range has yet to be determined in further research. Furthermore, the lifetime maps were used to locate defects in the surface near regions.

Introduction

For many modern power electronic devices epitaxial growth on top of a silicon carbide (SiC) substrates represents an important first step. The quality of the layer can strongly influence the quality of the subsequent process steps and, therefore, the performance of the whole device [1]. Defects like dislocations, stacking faults, and extrinsic point defects, which might be transferred from the substrate to the epitaxial layer or form in the layer itself can strongly restrict the possible device yield [1, 2]. Minority carrier lifetime is known to be sensitive to the presence of such defects, as well as to doping and thickness variations and surface and interface recombination [3]. Hence, lifetime measurements potentially offer a nondestructive and contactless way of monitoring the quality of the grown layer.

Experimental

Conventional 4H-SiC substrates with a diameter of 150 mm and a 4° off-axis orientation towards $[11\overline{2}0]$ from different vendors were used for epitaxy in multiwafer planetary reactors (AIXTRON G5 WW C and G10-SiC epitaxy reactors). The total thickness of the layers ranged between 10 and 14 µm, with a typical thickness deviation across individual wafers < 4 % σ/mean. The layers featured an n-type doping concentration between 8×10^{15} and 2×10^{16} cm^{-3} and a lateral doping deviation < 6.5 % σ/mean across the wafer area, which is common for typical 1,200 V epilayer stacks. A buffer layer of 1 µm thickness and doping concentration of 1×10^{18} cm^{-3} is included. The carrier lifetime of almost 300 epitaxial wafers has been determined by microwave detected photoconductivity decay (µ-PCD) measurements in a SEMILAB WT-2000. A laser pulse at a wavelength of 349 nm for 4 ns with 120 µJ per pulse and a raster size of 1 mm was used. An edge exclusion of 3 mm was applied to exclude edge effects.

Results and Discussion

Stability of the Measurement Technique.

To verify the stability of the measurement technique and the tool itself a daily release measurement was performed on the same wafer each morning. After calibrating the laser, the same four points in the sample center were being measured. The mean values of these four measurement points for each day are depicted in Figure 1. In this statistical process control (SPC) chart the measured values are controlled by an upper and lower specification limit as well as an upper and lower control limit. The former has been defined as ±8% to the mean value over all measurements. A deviation of the measured values outside of these limits can be used to explain irregularities in the measurement data that might occur on specific days. The control limits are defined as three times the standard deviation σ over and under the target value and represent the hard limitation for the usability of the tool.

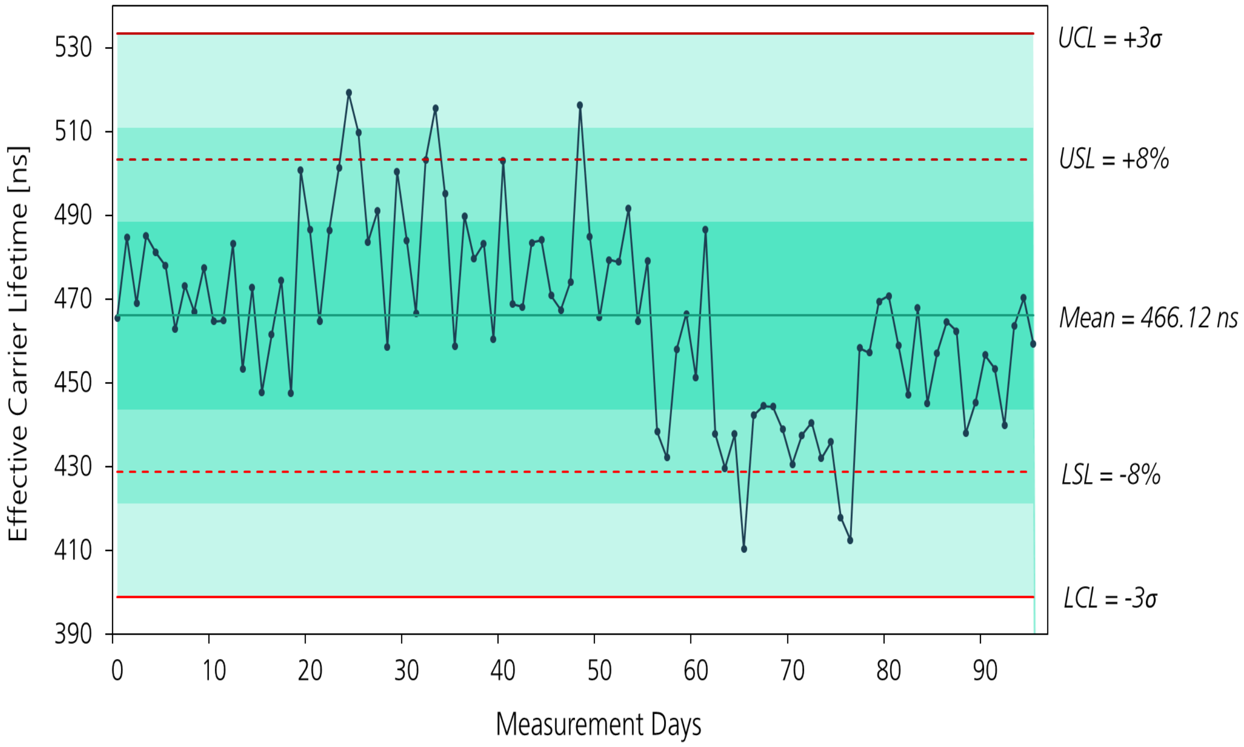

Fig. 1. Statistical process control (SPC) chart of daily µPCD measurements in the center of the same SiC sample with mean value, upper / lower spec limit (USL / LSL) and upper / lower control limit (UCL / LCL).

As can be seen in the SPC chart, in over 90 measurement days the spec limits have only been passed on a small number of days, while the control limits have never been breached. This confirms the reliable usage of this measurement process.

Statistical Overview of Lifetime Measurements.

Almost 300 epiwafers with 1,200 V epilayers have been analyzed using the µPCD technique. In Figure 2a) exemplary lifetime maps with a raster size of 1 mm for two samples with different lifetimes are presented. Qualitatively, they show the same radial dependence with higher carrier lifetimes in the center of the sample and a decrease towards the edges. However, the maximum value and the decline of lifetime is more pronounced for the sample on the right. Additionally, for all epiwafers, the lifetime has been averaged over the entire wafer area, and the results are statistically evaluated in the histogram in Figure 2b). These average lifetimes are divided in two different ranges: most samples exhibit an average carrier lifetime between 75 ns and 150 ns, while there is also a smaller number of samples with lifetimes around 250 ns. Both groups roughly resemble a Gaussian distribution, which is to be expected.

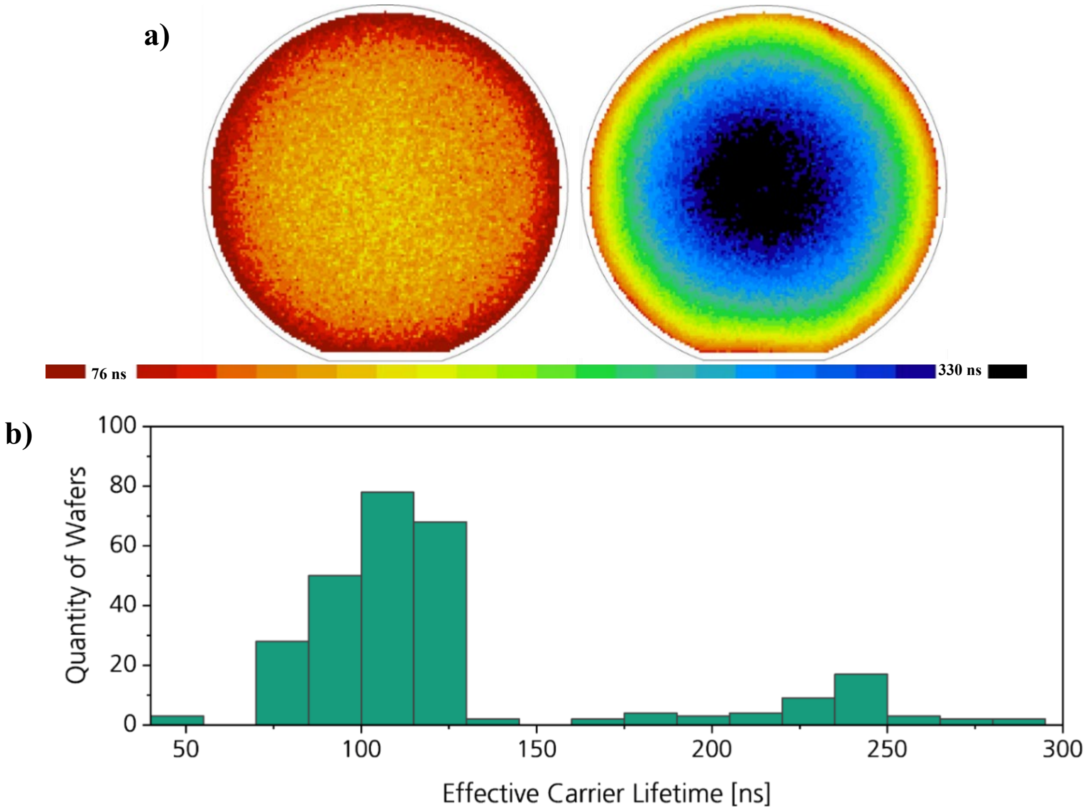

Fig. 2. a) Exemplary lifetime maps with 1 mm raster size from two samples with different lifetimes; b) Histogram of the average lifetimes on different SiC wafers, measured by µPCD.

According to Klein [3] effective carrier lifetimes in epilayers are dependent on four different recombination processes: Shockley-Read-Hall (SRH), radiative, Auger, and surface recombination, as seen in Equation (1):

$$\frac{1}{\tau_{meas}} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{Rad}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{Surf}} \tag{1}$$

For 4H-SiC at the given doping concentrations the radiative and Auger contributions can be neglected [3], leaving τ_{SRH} in the bulk and τ_{Surf} at the surface and the interface between epilayer and substrate. Kimoto et al. [4] showed that bulk lifetimes in epilayers dominated by SRH recombination can be estimated using the $Z_{1/2}$ concentration N_Z as following:

$$\tau_{SRH} = \frac{2\cdot 10^{13} cm^{-3}}{N_Z} \mu s \tag{2}$$

The surface contribution can be approximated using the epilayer thickness d, the carrier diffusion coefficient D, and the surface recombination velocity S, as reported by Klein [3]:

$$\frac{1}{\tau_{Surf}} = \left(\frac{d^2}{\pi^2 D} + \frac{d}{2S}\right)^{-1} \tag{3}$$

This results in the following Equation (4) for the measured carrier lifetime τ_{meas}:

$$\frac{1}{\tau_{meas}} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{Surf}} = \frac{N_Z}{2\times 10^{13} cm^{-3} \mu s} + \left(\frac{d^2}{\pi^2 D} + \frac{d}{2S}\right)^{-1} \tag{4}$$

Using the values for these parameters in Table 1, the measured carrier lifetime τ_{meas} can be approximated to **120.4 ns** at an epilayer thickness of 10 µm. This matches the left lifetime range in the histogram in Figure 2b). However, the cause for samples with lifetimes in the higher range could not be determined yet. A comparison between the average lifetime of the samples and their corresponding epilayer thickness, doping concentration, substrate resistivity, or substrate vendor did not result in any distinct correlation.

In fact, for some samples originating from adjacent regions of the same SiC ingot, which were coated side by side in the same epitaxy process and measured consecutively using the lifetime measurement tool, lifetime values were obtained that could be divided into the two different lifetime ranges.

Table 1. Parameters used to approximate the effective carrier lifetime in the measured samples.

$Z_{1/2}$ concentration N_Z	5×10^{12} cm^{-3} [5]
Epilayer thickness d	10 µm
Carrier diffusion coefficient D	4.2 cm^2/s [6]
Surface recombination velocity S	5×10^3 cm/s [3]

Lifetime and Defect Comparison.

The most probable cause for difference in the lifetime of different samples are defects in the epitaxial layer. In Figure 3 the lifetime maps of three different wafers are shown. Additionally, for each wafer a mapping of defects, recorded with a Lasertec SICA88, is included. It is noticeable that areas with higher density of defects have a strongly decreased carrier lifetime. Particularly stacking faults and polytype inclusions seem to have a strong influence. In the close ups of the Differential Interference Contrast (DIC) images, it is also recognizable that these areas with higher ratio of defects have a rougher surface compared to other areas of the wafers.

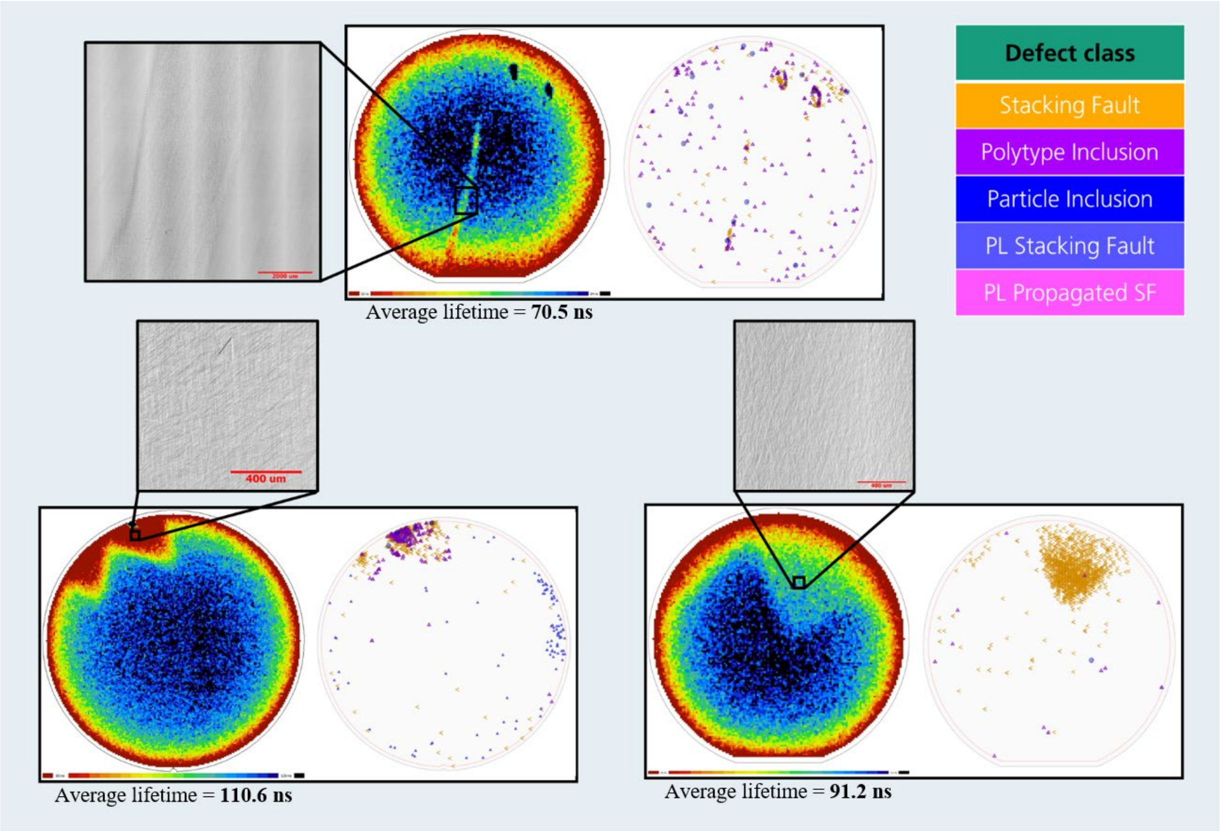

Fig. 3. Comparison of lifetime and defect maps as well as Differential Interference Contrast (DIC) images (recorded with Lasertec SICA88); average lifetime for each map is given.

Summary

The µPCD measurement technique offers a fast and non-destructive way of determining the effective lifetime of minority charge carriers in the epitaxial layer of 4H-SiC epilayer stacks. This can be used to gain information about the quality of the epilayers as well as the location and density of defects in the layer. With the use of the daily measurements the stability of the measurement tool can be controlled. Additionally, the lifetime values around 120 nm could be verified by theoretical calculations. However, the occurrence of the second lifetime range is still not fully understood. In further research the different types of defects and their density in samples from the different groups will be compared, to gather further insight into their impact on the charge carrier lifetime.

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