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Influence of Growth Temperature on Carrier Lifetime in 4H-SiC Epilayers

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Abstract. Carrier lifetime and formation of defects have been investigated as a function of growth temperature in n-type 4H-SiC epitaxial layers, grown by horizontal hot-wall CVD. Emphasis has been put on having fixed conditions except for the growth temperature, hence growth rate, doping and epilayer thickness were constant in all epilayers independent of growth temperature. An increasing growth temperature gave higher $Z_{1/2}$ concentrations along with decreasing carrier lifetime. A correlation between growth temperature and D_1 defect was also observed.

Introduction

For SiC to be interesting for high power and high voltage bipolar devices, a tailored minority carrier lifetime is crucial. Carrier lifetime can be significantly improved by post-growth processing, either by thermal oxidation [1] or by carbon implantation followed by annealing [2]. As demonstrated in [3], the $Z_{1/2}$ defect is proposed as the main lifetime-killing defect and is presumably related to a carbon vacancy. Other ways to improve carrier lifetime is to minimize the deep level concentrations through optimization of growth conditions. Intrinsic defect concentrations have been studied as function of growth conditions [4, 5], where low C/Si ratio and low growth temperature seem preferable for improving the carrier lifetime.

We have previously studied the influence of growth rate and C/Si ratio on carrier lifetime in 8° off-cut substrates [6]. In this study, we have extended the investigation to the influence of growth temperature on carrier lifetime and the formation of defects in the epilayers, grown on both 4° and 8° off-cut substrates. Large efforts have been made to keep fixed growth conditions, except for the growth temperature. Carrier lifetime was correlated to deep levels using deep level transient spectroscopy (DLTS) and other defects using low temperature photoluminescence (LTPL).

Experimental

Epitaxial layers of 4H-SiC were grown by horizontal hot-wall CVD on 4° and 8° off-cut 4H-SiC (0001) substrates. The substrates were cut in pieces in order to have comparable epilayers for each experimental series, with minimal influence of substrate quality. The cutting was done radially to avoid influence of radial variation in defect distribution. Precursors used were silane (SiH_4) and propane (C_3H_8) or ethylene (C_2H_4) in hydrogen carrier gas. Growth pressure was 100 mbar and growth temperature was varied between 1490 °C and 1610 °C for 8° off-cut substrates and between 1610 °C and 1670 °C for 4° off-cut substrates. The two sample series were grown in two different generations of VP508 reactors, with different susceptor designs and accordingly, two ways of reading the temperature. The pyrometer is either measuring the temperature directly on a spot on the sample carrier plate (8° off-cut) or in a hole in the susceptor below the rotating satellite (4° off-cut), which is rotating on an Ar gas cushion driven by a directed gas flow. Another difference is the susceptor coatings, which is either SiC coating (8° off-cut) or TaC coating (4° off-cut). N-type doping was achieved in the low to mid 10^{15} cm^{-3} range by adding nitrogen gas. In order to have

Fig. 1. Measured carrier lifetimes in epitaxial layers, grown at 1490 °C to 1610 °C on 8° off-cut 4H-SiC (0001) substrate. Gas flow direction is indicated by arrows.

Fig. 2. AFM images of 10 x 10 μm^2 areas with average RMS values indicated for 8° off-cut samples.

measured at room temperature by analyzing the time resolved photoluminescence decay of the near band edge emission, after excitation with 355 nm frequency-tripled Nd:YAG laser. Carrier lifetime mappings were done with a spatial resolution of 250 μm . For DLTS measurements, 1000 Å Ni contacts (1.2 mm diameter) served as Schottky contacts on the epilayers and conducting Ag paint served as Ohmic contact on the backside of highly doped substrate. DLTS spectra were obtained from 220 to 690 K or 220 to 400 K using a reverse bias of -10 V and 10 ms long and 10 V high filling pulses. The capacitance transients were acquired during 500 ms.

Results and discussion

The epitaxial growth temperature is found to directly influence the carrier lifetime and a significant lifetime improvement is observed by decreasing the growth temperature. In 8° off-cut epilayers carrier lifetime increases from 200 ns to 400 ns by decreasing the growth temperature from 1610 °C to 1490 °C (Fig. 1). On the other hand, surface roughness increased considerably by decreasing the growth temperature (Fig. 2). However, no major difference in epitaxial defect density is observed. Growth temperature outside of this range either resulted in polycrystalline material or too low growth rate for a given flow rate of precursors and C/Si ratio. The small gradient in carrier lifetime in epilayers grown at higher temperatures (Fig. 1) could possibly be due to temperature variations along the gas flow direction in the susceptor with non-rotating wafer geometry. However, a less pronounced carrier lifetime gradient is seen in epilayer grown at relatively low temperature of 1490 °C (Fig. 1).

A similar trend of the carrier lifetime with growth temperature has been observed in 4° off-cut epilayers grown in a TaC coated susceptor with wafer rotation. In this case, the carrier lifetime increases from 500 ns to 1500 ns in the temperature range 1670 °C to 1610 °C (Fig. 3). Carrier lifetime increased consistently from 500 ns to 1500 ns in the growth temperature range 1670 °C to 1630 °C, but it dropped down to 1000 ns at 1610 °C. All the epilayers in this series have a regular step structure, but there is no obvious tendency in the surface RMS values versus growth temperature (Fig. 4). However, a high epitaxial defect density is observed in the epilayer grown at 1610 °C, which is evident from large area local lifetime reductions visible in the lifetime map (Fig. 3). The reason for the significantly higher carrier lifetime in the layers grown in TaC coated susceptor with wafer rotation compared to the layers grown in SiC susceptor is not clear yet, but same tendency has previously been observed [7]. However, independent of the susceptor design and substrate off-cut, the trend in carrier lifetime with growth temperature is still the same.

comparable epilayers, growth rate and thickness were kept constant in all epilayers in each sample series. For 8° off-cut series the epilayer thickness was 50 μm grown at 6.5 $\mu\text{m/h}$ and for the 4° off-cut series the thickness was 40 μm grown at 10 $\mu\text{m/h}$. Epilayer thickness was measured by FTIR and doping was measured by C-V. Optical microscopy with Nomarski interference contrast was used to observe surface morphological defects and AFM was used to analyze surface topography and roughness. LTPL using the 244 nm line of an Ar^+ laser was used to observe presence of residual impurities and specially the D_1 intrinsic defect. Carrier lifetime was

Fig. 3. Measured carrier lifetimes in epitaxial layers, grown at 1610 °C to 1670 °C on 4° off-cut 4H-SiC (0001) substrate.

Fig. 4. AFM images of 10 x 10 μm² areas with average RMS values indicated for 4° off-cut samples.

Along with the decreased carrier lifetime with increasing temperature, increased $Z_{1/2}$ concentrations could be concluded from DLTS measurements. The $Z_{1/2}$ trap is found at about 0.68 eV below the conduction band edge and is always accompanied by the $EH_{6/7}$ trap, positioned 1.5 eV below the conduction band edge. For 8° off-cut, the measured $Z_{1/2}$ concentrations are shown in Fig. 5. The $Z_{1/2}$ concentration increases with growth temperature, indicating a correlation between $Z_{1/2}$ defect and carrier lifetime and its proposed property as a lifetime killing defect. The formation energy of the $Z_{1/2}$ defect was calculated from the Arrhenius plot in Fig. 6, giving a value of 3.1 eV, which corresponds rather well with theoretically calculated formation energy of carbon vacancies (V_C) in 4H-SiC under stoichiometric conditions of 4.07 - 4.21 eV, as modeled by Torpo [8]. The formation energy in our epilayer corresponds well with other experiments where the growth temperature is varied [5], but is slightly lower than those obtained from annealing experiments [9]. For the 4° off-cut experimental series conducted in the TaC coated susceptor with wafer rotation, only the two highest growth temperatures gave measurable concentrations of the $Z_{1/2}$ defect, $5.1 \times 10^{12} \text{ cm}^{-3}$ for 1650 °C and $6.6 \times 10^{12} \text{ cm}^{-3}$ for 1670 °C. $Z_{1/2}$ concentration in the epilayers grown at relatively low temperatures of 1610 °C and 1630 °C are below the detection limit of our DLTS setup. The increase in $Z_{1/2}$ concentration at high growth temperature follows the same tendency as observed in the 8° off-cut samples grown in SiC coated susceptor. Nevertheless, calculating the formation energy of the $Z_{1/2}$ defect, from the two measured defect concentrations, gives an energy of 4 eV corresponding well to the formation energy of carbon vacancies in 4H-SiC.

Fig. 5. Average $Z_{1/2}$ concentrations measured on several points in the center of the 8° off-cut samples.

Fig. 6. Arrhenius plot of temperatures 1520 °C to 1610 °C, giving the formation energy (3.1 eV) of the $Z_{1/2}$ defect for the 8° off-cut samples.

Fig. 7. LTPL spectrum showing an increased intensity of the D_1 defect with increasing growth temperature on the 8° off-cut samples.

Higher growth temperatures showed an increased D_1 intensity in the LTPL spectrum (Fig. 7). The origin of the D_1 defect is still not clear, but its intrinsic nature is clear from implantation and e-irradiation studies. In addition to the $Z_{1/2}$ defect, there is also a correlation between growth temperature and the D_1 defect in the grown epilayers and thus, D_1 could also be a lifetime influencing defect, as proposed in [10]. However, it could also be that the D_1 defect is formed under similar conditions as other lifetime limiting defects.

Summary

In conclusion, lower growth temperatures are advantageous to obtain longer carrier lifetimes. The same trend in the carrier lifetime variations with growth temperature was observed in both 8° and 4° off-cut grown epilayers. However, the carrier lifetime is significantly longer in epilayers grown in the reactor with TaC coated susceptor and with wafer rotation. We have observed an increase of both the concentration of the $Z_{1/2}$ and the intensity of the D_1 defect from LTPL, with increasing growth temperature. The difference in measured lifetime between the two reactors is also consistent with the difference in $Z_{1/2}$ concentration, supporting the assumption of $Z_{1/2}$ as the main lifetime limiting defect. From the calculations of the formation energies of $Z_{1/2}$ defect, it is consistent with the proposed relation to carbon vacancies. The lower D_1 concentration in epilayers with comparatively long minority carrier lifetime indicates the possibility of D_1 as a lifetime influencing defect along with $Z_{1/2}$.

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