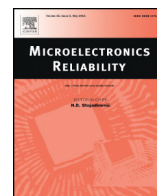




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Carbon-related defects in microelectronics

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ABSTRACT

In the present study electrically active carbon and hydrogen-related (CH) defects, which can act as strong recombination centers in high power devices and CMOS photodetectors, are investigated in *n*-type Si. Several different CH-related defects are observed by using the deep level transient spectroscopy (DLTS) technique on hydrogenated Si samples with different oxygen content. The concentration of these defects is determined as low as 10^{12} – 10^{13} cm⁻³. By comparing samples with different O, C, and H concentrations the origin of the CH-related defects is derived. We show that the concentration of the electrically inactive substitutional C can be estimated by a comparison of the depth profiles of the electrically active CH-related defects in a sample with those in a reference sample which has an identical oxygen and known carbon content. This approach is applicable even for concentrations of substitutional C lower than 10^{15} cm⁻³.

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1. Introduction

The presence of unintentionally introduced defects, such as substitutional carbon (C_s) and interstitial oxygen (O_i), can significantly influence the electrical properties of electronic devices. Being electrically inactive in Si these defects can create electrically active complexes with hydrogen or native defects (vacancies or interstitials), which are introduced in various device processing steps, e.g. by implantation or by heat treatments of Si wafers in hydrogen (H) containing atmosphere. These electrically active complexes can also act as recombination centers in Si and, therefore, significantly decrease the lifetime of minority carriers. As a result, with the appearance of novel high power devices, transistors and CMOS photodetectors the control over C- and O-related defects becomes an important task in modern microelectronics [1,2]. In photovoltaics, the increase of the cell efficiency and the reliability of solar cells is also inseparably linked with the reduction of the concentration of strong recombination centers. Therefore, all these devices require high quality materials with low concentrations of unintentionally introduced impurities for optimum performance and reliability.

In modern devices the conventional detection of substitutional C by the Fourier transform infrared absorption (FTIR) technique is limited to concentrations above 10^{15} cm⁻³ [3], which can become insufficient for their faultless functioning. In contrast, the deep level transient spectroscopy (DLTS) technique [4] allows the detection of electrically active deep level defects with concentrations as low as 10^{11} – 10^{12} cm⁻³, depending on the doping concentration. However, in this technique the

preparation of contacts is necessary, and this could be undesired in some cases. In addition, depending on the doping level of the semiconductor only a narrow range below the surface can be analyzed with the DLTS technique. This can be a critical limitation, e.g. if non-uniform depth profiles are under investigation.

In the present study we use DLTS to analyze electrically active carbon-hydrogen (CH) related defects, which introduce deep levels into the band gap of Si after hydrogenation by wet chemical etching or a dc hydrogen plasma treatment. Carbon containing samples with different oxygen and hydrogen concentrations are investigated. We show that the presence of oxygen can significantly modify the DLTS spectra and that some novel COH-related defects can be observed. By comparing samples with similar doping levels and an identical oxygen content information about the concentration of electrically inactive C_s can be obtained.

2. Experimental procedure

Samples were cut from different *n*-type Czochralski (CZ) Si wafers supplied by different vendors. The doping level in all samples was about 1×10^{15} cm⁻³ and they contained different concentrations of carbon and oxygen. The concentration of transition metals in these samples was below the detection limit of our DLTS setup ($\sim 10^{11}$ cm⁻³), as measured in samples prepared without hydrogenation. Hydrogen was introduced either by wet chemical etching (WCE) at room temperature for 2–5 min in an acid consisting of HNO₃:HF:CH₃COOH with a volume ratio of 5:3:3 or by a dc H plasma treatment at 320 K. Schottky diodes were produced by resistive evaporation of Au in vacuum onto the polished side of the samples at room temperature. Ohmic contacts were prepared by rubbing the back side of the samples with an eutectic

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InGa alloy. The quality of the Schottky and Ohmic contacts was characterized by current-voltage (I - V) and capacitance-voltage (C - V) measurements in the range of 50–300 K. Laplace DLTS with two filling pulses [5] was employed in order to investigate the electronic properties (activation enthalpy and capture cross section) of deep levels and their depth profiles. The depth profiles were recorded by keeping the reverse bias constant while varying the two filling pulses. The labeling of the DLTS peaks in this work corresponds to the temperatures at which these peaks were observed in the DLTS spectra for an emission rate of 48 s^{-1} .

3. Results

Fig. 1 shows DLTS spectra recorded in two samples with different oxygen concentrations: $5 \times 10^{15} \text{ cm}^{-3}$ (a) and $1 \times 10^{18} \text{ cm}^{-3}$ (b). The substitutional carbon concentration in these samples was about $5 \times 10^{15} \text{ cm}^{-3}$. The samples were subjected to the hydrogenation by wet chemical etching at room temperature (closed symbols) or by a dc H plasma treatment (open symbols). After WCE only a single peak E90 was observed in a sample with the lower O content (Fig. 1a).

The concentration of this defect was about $2 \times 10^{12} \text{ cm}^{-3}$ at around $4 \mu\text{m}$. In contrast, three DLTS peaks E42, E90, and E262 can be distinguished in the spectrum after a dc H plasma treatment of a sample cut from the same wafer. One should emphasize that the intensity of E90

was only coincidentally identical in both DLTS spectra after WCE and after a dc H plasma treatment since different regions were probed in these samples. Although the intensity of the DLTS peaks E42 and E262 in Fig. 1(a) differs significantly their concentrations are found to be identical (about $2 \times 10^{13} \text{ cm}^{-3}$ at a depth of around $1 \mu\text{m}$). This can be explained by different values of the width of the lambda-layer [6] at 42 K and 262 K, and by a contribution of the freeze-out effect of the net carrier concentration at the lower temperature.

The thermal stability of E42 and E262 was investigated by 60 min isochronal annealing experiments. The samples were annealed in air at temperatures between 280 K and 420 K and the concentration of the defects was determined always at the same depth of about $1.7 \mu\text{m}$. Within the experimental accuracy we found that the annealing temperatures of E42 and E262 were identical [8]. The intensities of the peaks were reduced by a factor of two at about 375 K and they annealed out at about 420 K.

The concentration of E42, E90, and E262 was found to be proportional to the H content in hydrogenated Si. The H content in the samples can be estimated by analyzing the depth profiles of shallow impurities (phosphorous for n -type Si) as calculated from C - V measurements. Due to the passivation of shallow donors by isolated H the net free carrier concentration in hydrogenated samples is lower than in as-grown samples. The more hydrogen is introduced the lower concentration of the net free carrier concentration should be observed.

We did not observe any increase of the intensity of the DLTS peaks in Fig. 1(a) by increasing the oxygen content in our samples. However, their intensity increases with increase of the substitutional C-concentration.

The electrical properties (activation enthalpy and apparent capture cross section) of E42, E90, and E262 were obtained from the Arrhenius plots (see Fig. 2) and they are combined in Table 1.

In the samples with a higher O content (Fig. 1(b)) the intensity of E90 was significantly reduced compared to samples with a lower O concentration, and two novel DLTS peaks E65 and E75 appeared in the DLTS spectrum after WCE. The electrical properties of the defects corresponding to these peaks were obtained from the Arrhenius plots and they are also presented in Table 1.

The annealing behavior of E65 and E75 was investigated by 30 min isochronal annealing steps in air (see Fig. 3). In this figure the concentrations are normalized to the initial concentrations recorded at room temperature directly after a dc H plasma treatment. The annealing curves of E65 and E75 were similar: their intensities were reduced by a factor of two at about 360 K and they annealed out at about 400 K.

Similar to the DLTS peaks in Fig. 1(a) the intensities of E65 and E75 also increased if more H was introduced into the samples. The

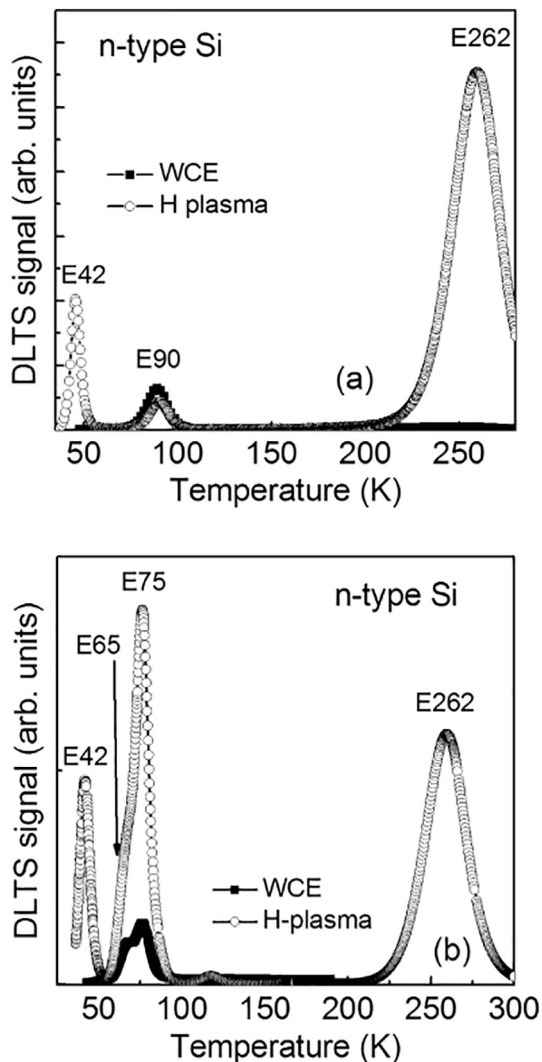


Fig. 1. DLTS spectra recorded in two samples with different O contents: $5 \times 10^{15} \text{ cm}^{-3}$ (a) and $1 \times 10^{18} \text{ cm}^{-3}$ (b) after WCE and a dc H plasma treatment.

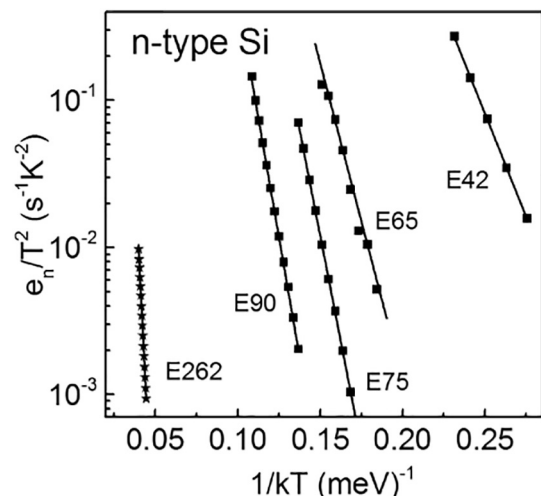


Fig. 2. Arrhenius plots recorded for the traps observed in Fig. 1.

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