Linköping University Post Print

Metastable defects in low-energy electron irradiated n-type 4H-SiC

Franziska Beyer, Carl Hemmingsson, Henrik Pedersen, Anne Henry, Junichi Isoya, Norio Morishita, Takeshi Ohshima and Erik Janzén

N.B.: When citing this work, cite the original article.

Metastable defects in low-energy electron irradiated n-type 4H-SiC

Franziska C. Beyer[1,a], Carl Hemmingsson[1,b], Henrik Pedersen[1,2,c], Anne Henry[1,d], Junichi Isoya[3,e], Norio Morishita[4,f], Takeshi Ohshima[4,g], Erik Janzén[1,h]

[1]Department of Physics, Chemistry and Biology, Linköping University, SE-58131 Linköping, Sweden
[2]Sandvik Tooling Sverige AB R&D, Lerkrogsvägen 19, SE-126 80 Stockholm, Sweden
[3]Graduate School of Library, Information and Media Science, University of Tsukuba, 1-2 Kasuga, Tsukuba, Ibaraki 305-8850, Japan
[4]Japan Atomic Energy Agency, 1233 Watanuki, Takasaki, Gunma 370-1292, Japan

[a]fbeyer@ifm.liu.se, [b]cah@ifm.liu.se, [c]henrik.pedersen@sandvik.com,
[d]ahy@ifm.liu.se,[e]isoya@slis.tsukuba.ac.jp, [f]morishita.norio@jaea.go.jp,
[g]ohshima.takeshi20@jaea.go.jp, [h]erj@ifm.liu.se

Keywords: metastable defects, bistability, electron irradiation, DLTS

Abstract. After low-energy electron irradiation of epitaxial n-type 4H-SiC, the DLTS peak amplitudes of the defects $Z_{1/2}$ and EH6/7, which were already observed in as-grown layers, increased and the commonly found peaks EH1 and EH3 appeared. The bistable M-center, previously seen in high-energy proton implanted 4H-SiC, was detected. New bistable defects, the EB-centers, evolved after annealing out of the M-center, EH1 and EH3. The reconfiguration energies for one of the two EB-centers were determined to be about 0.96 eV for both transitions: from configuration I to II and from configuration II to I. Since low-energy electron irradiation (<220 keV) affects mainly the carbon atom in SiC, both the M- and EB-centers are likely to be carbon related defects.

Introduction

Electron irradiation can be used to intentionally introduce intrinsic defects in semiconductors. Their electronic properties can be studied by deep level transient spectroscopy (DLTS). Additional characterization techniques can finally give information about the structure and the chemical identity of the defects. DLTS studies on high-energy electron irradiated SiC showed the introduction of several defects [1] and in high-energy proton implanted SiC an additional bistable defect, the M-center [2], has been observed. Due to high-energy of the impinging particles, both silicon and carbon atoms may be displaced and, thus, give rise to both silicon and carbon related defects. On the other hand, low-energy electron irradiation (<220 keV), is commonly assumed to only affect C-atoms in SiC [3]. Recently a new bistable defect, the EB-center, which is investigated further in this study has been reported [4] after low-energy electron irradiation.

Experiments

A 200-μm-thick low-doped n-type 4H-SiC epilayer was homo-epitaxially grown on a highly doped n-type substrate using chloride based chemical vapour deposition in a horizontal hot wall reactor. More details concerning growth and layer characterization can be found in [5].
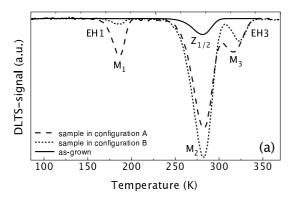
The sample was cut in several pieces, and some of them were irradiated by low-energy electrons (200 keV) at room temperature with a dose of $5 \cdot 10^{16}$ cm^{-2}. For electrical measurements, Ni-Schottky contacts were thermally evaporated onto the surface after chemical cleaning and short HF dip of the samples. The Schottky contacts' diameter were 1200 μm and 800 μm. Conducting silver paint served as ohmic backside contact. Capacitance voltage measurements at room temperature showed a homogeneous doping profile with a net doping concentration of $N_d - N_a \approx 1 \cdot 10^{15}$ cm^{-3}. DLTS was performed in the temperature range 85 to 700 K. Following DLTS parameters were used: filling pulse height of 10 V with a length of 10 ms, transient record time of 500 ms under reverse bias condition ($V_r = -10$ V). Heat treatments were performed directly in the DLTS cryostat under atmospheric conditions, thus annealing with or without bias applied to the sample was possible. Isochronal annealing was achieved by increasing the annealing temperature by 5 K steps, while keeping the annealing time constant at $t_{anneal} = 1$ min. Contrary, for isothermal annealing, the temperature was constant and the annealing time increased.

Results and Discussion

As discussed in [4], the frequently detected irradiation induced DLTS peaks EH1 and EH3 (labeled S1 and S2, respectively in [2]) were detected in the DLTS spectra after low-energy electron irradiation. The defect concentrations of the intrinsic defects $Z_{1/2}$ and EH6/7, which were already observed before irradiation, increased by one order of magnitude after irradiation. It should be pointed out that the ratio between the defect concentrations of $Z_{1/2}$ to EH6/7 stayed constant $\approx 1 : 1$ independently of irradiation, thus an equal defect generation rate of both defects is assumed and the origin of these defects is likely related to carbon, either as interstitials, vacancies and/or their complexes.

Fig. 1 (a) shows the DLTS spectra of the M-center observed in low-energy electron irradiated 4H-SiC. This bistable center was first detected in high-energy proton implanted 4H-SiC [2]. Configuration A, which gives rise to the DLTS peaks M1 and M3, is dominant under most conditions while configuration B, which gives rise to the DLTS peak M2, can be reached only if the sample is first heated up to over 420 K followed by cooling down to the DLTS starting temperature without any bias applied to the sample. Since the M-center is already present in the DLTS spectra after low-energy electron irradiation, the origin of the M-center is associated with carbon related intrinsic defects. The annealing out temperature (650 K) as well as the reconfiguration temperatures (A→B: ≈ 450 K, B→A: ≈ 290 K) of the M-center were in good agreement with what was reported by Martin et al. [2]. During the annihilation process of the M-center, EH1 and EH3, new peaks occurred in the DLTS spectra depending on whether the annealing was carried out with or without bias applied to the sample.

Fig. 1 (b) shows low temperature DLTS spectra of the newly detected peaks, labeled EB1 to EB5 in the spectra. The two configurations I and II were obtained by selecting different bias conditions above room temperature and then cooling down to the DLTS starting temperature. With bias applied to the sample, defects are stabilized in configuration I and without bias in configuration II. Configuration I gives rise to EB4 and EB5 peaks (solid line) and configuration II gives rise to EB1, EB2 and EB3 peaks (dotted line). As it can be seen from the DLTS spectrum the EB5 peak is quite broad and asymmetric and consists possibly of more than one peak. The defect concentrations of the EB peaks, determined from the DLTS peak amplitude are in the low 10^{12} cm^{-3} range. The properties of these defects can be found in Table 1.
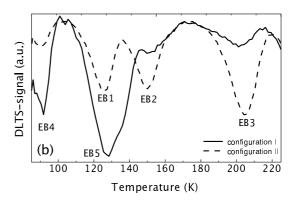
Fig. 1: DLTS spectra of low-energy electron irradiated n-type 4H-SiC sample. **(a)** bistable M-center in configuration A (dotted line) and B (small dotted line). The solid line represents the DLTS spectrum of the as-grown epilayer. **(b)** low temperature DLTS spectra after the annealing out of the M-center, EH1 and EH3. Bistable EB-centers in configuration I (solid line) and II (dotted line). DLTS parameters: rate window $(3.2 \text{ s})^{-1}$, $t_p = 10$ ms, $V_r = -10$ V.

Table 1: Properties of the EB-centers. Energies and capture cross sections are obtained from Arrhenius plots ($\ln(e/T^2)$ versus $1000/T$) and concentrations from the DLTS peak amplitudes.

configuration	peak	activation energy (eV)	capture cross section (cm^2)	trap concentration (cm^{-3})
II	EB1	$E_C - 0.26$	$3 \cdot 10^{-15}$	$2.1 \cdot 10^{12}$
II	EB2	$E_C - 0.34$	$2 \cdot 10^{-14}$	$2.0 \cdot 10^{12}$
II	EB3	$E_C - 0.44$	$4 \cdot 10^{-15}$	$2.6 \cdot 10^{12}$
I	EB4	$E_C - 0.19$	$2 \cdot 10^{-15}$	$2.3 \cdot 10^{12}$
I	EB5	$E_C - 0.27$	$2 \cdot 10^{-15}$	$3.3 \cdot 10^{12}$

The signal amplitude of peaks EB4 and EB3 is about the same height, as well as the calculated defect concentrations (see Table 1). The total defect concentration of EB1 and EB2 peak is similar to the concentration of EB5, taking the small shoulder at the higher temperature side into account. Thus, the EB peaks might be related to two bistable defects, one giving rise to the peaks EB3 and EB4 while the other one giving rise to the peaks EB1, EB2 and EB5. As the EB-centers occurred after annealing of low-energy irradiated 4H-SiC, they may be associated with carbon intrinsic defects.

The reconfiguration behavior of the EB-centers was studied by isochronal annealing. Fig. 2 (a) and (b) shows the fraction of defects in the different configurations versus annealing temperature under different bias conditions. The fraction was determined by studying the DLTS peak amplitudes of EB3 (configuration II) and EB4 (configuration I), which belongs to one of the two EB-centers. In (a) the EB-center was stabilized in configuration I prior to the annealing and in (b) in configuration II. As it can be seen, the transitions from configuration I to II as well as from II to I both take place at about room temperature. The other EB-center, not shown here, changes its configuration at about the same temperature.

The reconfiguration energy for this EB-center was determined from an isothermal annealing study, where the amplitudes of the EB4 peak for configuration I and the EB3 peak for configuration II were followed. The activation energies, E_a for the transition from configuration I to II
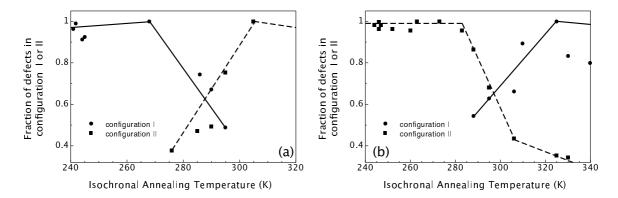
Fig. 2: Isochronal annealing of one of the EB-centers; **(a)** with bias ($V_r = -10$ V), defects initially in configuration I and **(b)** without bias ($V_r = 0$ V), defects initially in configuration II (the lines are only guides for the eyes).

and from configuration II to I were obtained from the logarithms of the reconfigurations rates, $\ln R$ versus $1/k_B T$ plot to be $E_a(\text{I} \to \text{II}) = 0.96$ eV and $E_a(\text{II} \to \text{I}) = 0.95$ eV.

Summary and conclusion

DLTS investigations were performed on n-type 4H-SiC samples, irradiated by low-energy electrons. After irradiation the bistable M-center, which was previously detected in high-energy irradiated samples, was observed. Its reconfiguration temperatures as well as the annihilation temperature were confirmed. During the annealing process new bistable defects, the EB-centers evolved in the low temperature range of the DLTS spectrum. The EB-centers change their configuration at an annealing temperature around 290 K. The activation energies for transformation were determined to be 0.96 eV from configuration I to II and 0.95 eV from configuration II to I for one of the two EB-centers. The origin of the EB-centers as well as the M-center is suggested to be related to carbon intrinsic defects.

Acknowledgments

References

[1] C. Hemmingsson, N. T. Son, O. Kordina, J. P. Bergman, E. Janzén, J. L. Lindström, S. Savage, and N. Nordell: J. Appl. Phys. Vol. 81 (1997), p. 6155–6159

[2] D. M. Martin, H. Kortegaard-Nielsen, P. Lévêque, A. Hallén, G. Alfieri, and B. G. Svensson: Appl. Phys. Lett. Vol. 84 (2004), p. 1704–1706

[3] J. W. Steeds, F. Carosella, A. G. Evans, M. M. Ismail, L. R. Danks, and W. Voegeli: Mater. Sci. Forum Vol. 353-356 (2000), p. 381–384

[4] F. C. Beyer, C. Hemmingsson, H. Pedersen, A. Henry, J. Isoya, N. Morishita, T. Ohshima, and E. Janzén: submitted to Physica Scipta (2009)

[5] H. Pedersen, S. Leone, A. Henry, A. Lundskog, and E. Janzén: Phys. stat. sol. (RRL) Vol. 2 (2008), p. 278–200