Solid-State Electronics 94 (2014) 32–38

Contents lists available at ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

ON-state characteristics of proton irradiated 4H–SiC Schottky diode: The calibration of model parameters for device simulation

J. Vobecký [a,b,*], P. Hazdra [a], V. Záhlava [a], A. Mihaila [c], M. Berthou [d]

[a] Department of Microelectronics, Faculty of Electrical Engineering, Czech Technical University in Prague, Technická 2, CZ-16627 Prague 6, Czech Republic
[b] ABB Switzerland Ltd., Semiconductors, Fabrikstrasse 3, CH-5600 Lenzburg, Switzerland
[c] ABB Switzerland Ltd., Corporate Research, Segelhofstrasse 1K, CH-5405 Baden, Switzerland
[d] Centro Nacional de Microelectrónica, CNM-CSIC, Campus UAB, 08193 Bellaterra, Barcelona, Spain

ARTICLE INFO

Article history:
Received 27 August 2013
Received in revised form 6 January 2014
Accepted 3 February 2014
Available online 22 February 2014

The review of this paper was arranged by Prof. S. Cristoloveanu

Keywords:
Silicon carbide
Schottky diode
Device simulation
Calibration
Radiation defects

ABSTRACT

4H silicon carbide Schottky diodes were irradiated by 550 keV protons with the aim to place the ion range into the low-doped *n*-type epitaxial layer. The diodes were characterized using DLTS, *C–V* profiling and forward *I–V* curves. Calibration procedure of model parameters for device simulation has been carried out. It is based on modeling the doping compensation of the *n*-type epitaxial layer caused by the deep acceptor levels resulting from radiation damage. It is shown that the agreement of simulated and measured forward *I–V* curves of proton irradiated diodes can be achieved, if the profiles of deep levels are calibrated with respect to irradiation dose, the degradation of electron mobility due to charged deep levels is accounted of and the Schottky barrier height is properly adjusted. The proposed methodology introduces a starting point for exact calibration of ion irradiated SiC unipolar devices.

1. Introduction

Wide band gap, high electrical strength, thermal conductivity and radiation hardness of devices processed from silicon carbide (SiC) offer improved ratings in the applications of power diodes [1] and radiation detectors [2]. Among many SiC polytypes, the 4H-SiC is particularly suitable for vertical devices because of high electron mobility and small anisotropy.

The electrical parameters of bipolar devices can be deteriorated by the presence of point defects, which cause carrier trapping, increased leakage current, and reduction in minority carrier lifetimes [3]. The dominant carrier lifetime limiting defect in as-grown *n*-type 4H–SiC material has been associated with the Z1/2 deep level [4]. This defect is already present in as-grown 4H–SiC and is considered to be of intrinsic nature with a relation to carbon. The concentration of the Z1/2 center, which was recently identified as a double-acceptor level of carbon vacancy [5], can be further increased after either ion or electron irradiation [6].

The existence of deep levels also affects the majority carrier devices like Schottky diodes. This can be for example due to the deep levels from the radiation damage after a high-energy ion irradiation, when these defects are strongly localized at the end of ion range. In the lower doped *n*-type drift regions processed by an epitaxy growth, the concentration of background doping becomes easily comparable with that of the radiation defects. Since they are of acceptor type, like the above mentioned Z1/2, the compensation of doping takes place and the original values of electrical parameters, like forward voltage drop, are deteriorated.

The compensation effect in proton-irradiated *n*-type 4H–SiC Schottky diode was studied in order to conclude that deep level Z1/2 has an intrinsic nature [7]. The energy of the protons was chosen such that the damage was uniformly distributed across the whole epitaxial layer. The aim of this paper is to account for the impact of the proton irradiation on the doping compensation of the epitaxial layer when the ion range (peak of the radiation damage) is placed directly into this layer and the originally constant doping concentration is locally reduced and made non-uniform. Based on the deep level transient spectroscopy (DLTS) and capacitance–voltage (*C–V*) measurements, the radiation damage is characterized in a way that the parameters of the Shockley–Read–Hall (SRH) and carrier mobility models can be calibrated

* Corresponding author at: ABB Switzerland Ltd., Semiconductors, Fabrikstrasse 3, CH-5600 Lenzburg, Switzerland. Tel.: +41 58 586 1769.
E-mail address: jan.vobecky@ch.abb.com (J. Vobecký).

http://dx.doi.org/10.1016/j.sse.2014.02.004
0038-1101/

to provide the device simulation with predictive capability. The calibration concept for simulation of forward *I–V* curves is demonstrated on the 4H–SiC Schottky diodes with breakdown voltage of 1.2 kV [8]. The simulation is performed using the Sentaurus Device platform from Synopsys [9] with the goal of increasing the TCAD software predictability for wide bandgap device simulation.

2. Experimental

4H–SiC Schottky diodes were processed and subsequently subjected to proton irradiation. Forward *I–V* curves were measured before and after irradiation to evaluate the impact on diode operation. Reverse bias *C–V* and DLTS measurements were combined with the simulation of radiation damage to provide the input parameters for models accounting for the proton irradiation of SiC in device simulation. The parameters of relevant models have been calibrated for quantitative agreement of measured and simulated forward *I–V* curves at room temperature. The details are summarized below.

2.1. Device under test

Schottky barrier diodes were fabricated at CNM Barcelona [8] using Cree™ 4H–SiC n^+ substrates covered with 13 μm thick *n*-type epilayer doped to $\approx 5 \times 10^{15}$ cm^{-3} by nitrogen. The Schottky barrier was made by a thin sputter deposited tungsten layer at the wet etched openings in SiO_2, which were subsequently covered by 3 μm thick aluminum contact. The diodes were provided with junction termination and passivation layers in order to achieve the breakdown voltage of 1.2 kV. The device active area is about 2.1×2.1 mm^2.

2.2. Ion irradiation

The diodes were irradiated through the anode side metallization with 550 keV protons using 3MV Tandetron accelerator. The irradiation doses were chosen in the range from 5×10^9 to 4×10^{10} cm^{-2} to preserve the validity of the Deep Level Transient Spectroscopy (DLTS) method. The irradiation formed a damaged layer located up to 2 μm below the silicon carbide surface in the *n*-type epilayer (see Fig. 1).

The radiation defects were characterized by capacitance DLTS using DLS-82E and DLS-83D spectrometers from SEMILAB Inc. The first measurement provided the spectra of *As irradiated*, i.e. not annealed devices see Fig. 2. Because the radiation defects anneal during the DLTS measurement performed up to 650 K, the repeated DLTS measurements were performed after the annealing at 350 °C for 60 min, which was necessary for defect stabilization – see the spectra *Annealed at* 350 °C in Fig. 2. High relaxation voltage V_R = 40 V and long excitation time t_{exc} = 10 ms were set to monitor all electron traps up to the depth of approx. 2.7 μm, i.e., beyond the damage maximum. *C–V* profiling provided the doping profiles of the *n*-type epilayers after proton irradiation – see Fig. 3(a). These profiles are used for the calibration of deep level concentration profiles for device simulation.

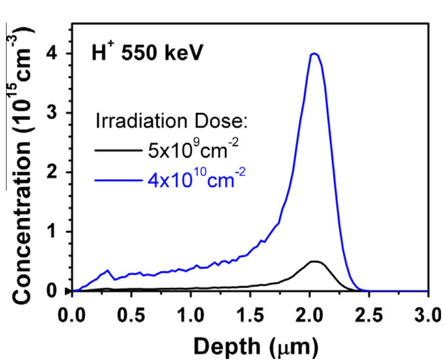

Fig. 1. Distribution of radiation defects (profiles of deep levels entered into the Shockley–Read–Hall model of device simulator) in the *n*-epilayer after proton irradiation. Proton irradiation dose is a parameter. Simulated using Monte Carlo code SRIM.

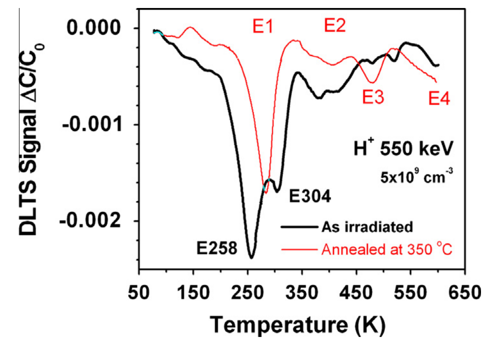

Fig. 2. DLTS spectrum measured after irradiation (bold) and post-irradiation annealing at 350 °C (thin), V_R = 40 V, V_{exc} = 0 V, t_{exc} = 10 ms, rate window 4.1 s^{-1}.

3. Device simulation

For device simulation the drift–diffusion approximation of the finite-element device simulator *Sentaurus Device* from Synopsys is used [9]. This simulator adequately supports the set of the

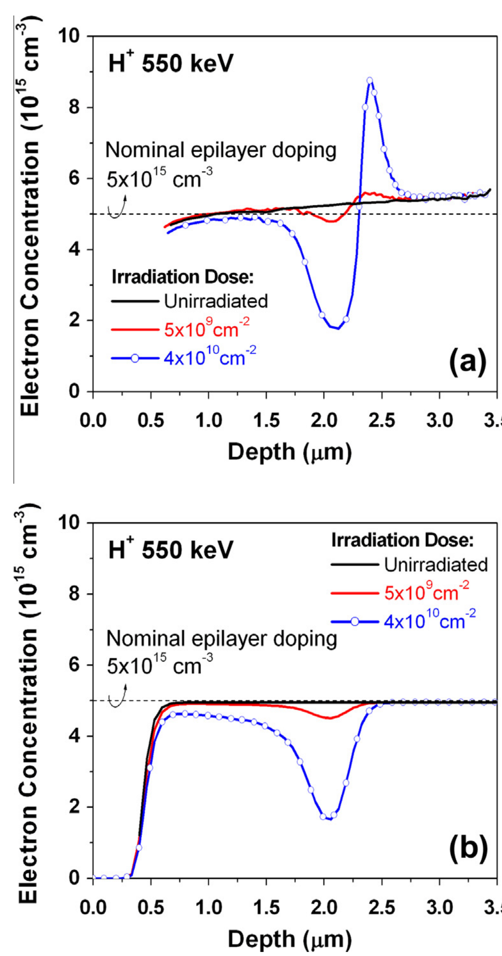

Fig. 3. Profile of free carriers in the *n*-type epilayer from the *C–V* measurements (a) and device simulation (b) of unirradiated and proton irradiated diodes.