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Characterization of deep electron traps in 4H-SiC Junction Barrier Schottky rectifiers

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ABSTRACT

Conventional deep level transient spectroscopy (DLTS) technique was used to study deep electron traps in 4H-SiC Junction Barrier Schottky (JBS) rectifiers. 4H-SiC epitaxial layers, doped with nitrogen and grown on standard n^{+}−4H-SiC substrates were exposed to low-dose aluminum ion implantation process under the Schottky contact in order to form both JBS grid and junction termination extension (JTE), and assure good rectifying properties of the diodes. Several deep electron traps were revealed and attributed to impurities or intrinsic defects in 4H-SiC epitaxial layers, on the basis of comparison of their electrical parameters (i.e. activation energies, apparent capture cross sections and concentrations) with previously published results.

1. Introduction

Silicon carbide (SiC) is an attractive wide bandgap semiconductor of a great current interest, because of its excellent material properties, such as high breakdown voltage, high power operations capability, high thermal conductivity and high radiation hardness. Due to these properties, SiC is widely used for high-power and high-frequency device applications operating under harsh environments, i.e. at much higher temperatures and higher radiation hardness compared to Si [1,2]. However, various factors currently limit further applications of SiC, including a quality, size and cost of available substrates or anomalous electrical characteristics of SiC-based devices.

There are many reports concerning inhomogeneities of the Schottky barrier height (SBH) between individual diodes and over one diode for titanium, nickel or platinum Schottky contacts [3–9]. A consequence of this phenomenon is that the forward characteristics of the diode become anomalous with unusually excess current at low-voltage levels and an ideality factor higher than unity. In the reverse characteristics, a large reverse leakage current and premature electrical breakdown are frequently observed for SiC Schottky diodes. It was suggested that these non-ideal characteristics result from localized lower barrier height areas within a large area diode with higher barrier height background. These areas are related to discrete structural or surface defects and imperfections of SiC material [3–9]. Alternative explanations involving generation recombination current, interfacial layers and edge effects related to the diode periphery are usually ruled out [5].

Despite, a great deal of efforts has been made to identify the source defects of observed SBH inhomogeneities, various device structures [2,10–12] and post-growth processes (e.g. thermal annealing, ion implantation, electron irradiation) [13–17] have been developed to reduce non-idealities and to improve efficiency of SiC-based devices. High- and low-energy particle irradiation (with electrons or protons), high thermal treatment or ion implantation processes of SiC are always the important field of study, both due to a interesting physics of defects and to its technological applications, such as charge-carrier lifetime control in bipolar devices, doping mechanism and controlling of density and properties of electrically active defects. The another idea is to design a specific device structure, which can offer better electrical characteristics than basic SiC power rectifiers, such as high switching speed with low reverse-recovery charge and high blocking voltage with low leakage current. The examples of such devices are Junction Barrier Schottky (JBS) [2,10] and Dual-Metal Trench [2,11] or Trench MOS Barrier Schottky (TMBS) [2,12] diodes.

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The JBS rectifier, firstly demonstrated in silicon [18], is a Schottky structure with p^+n junction grid integrated into its drift region, thus combining Schottky and PiN diode structures making use of advantages of both types. 4H-SiC JBS diodes show usually higher blocking voltage than Schottky diodes and offers nearly zero reverse-recovery charge [10]. This may be explained by the different blocking mechanisms (p^+n junction vs Schottky junction) and it shows that the JBS design is less sensitive to imperfections and crystal defects in state-of-the-art SiC material. Furthermore, such a structure can efficiently pinch off a low SBH region by a high SBH of the Schottky contact. In forward conduction mode, a current flows unipolarly through multiple conductive channels under the Schottky contact with a voltage drop determined by metal–semiconductor Schottky barrier height. In reverse blocking mode, p^+n junctions become reverse biased and depletion layers spread into the channel and pinch off the Schottky barrier.

In this paper, several *n*-type 4H-SiC JBS rectifiers were studied by means of conventional DLTS method [19]. A low-dose aluminum ion implantation process was used in order to obtain both JBS grid structure and JTE, and assure good rectifying properties of the studied diodes. The thorough analysis of the DLTS results makes possible to establish the fundamental parameters (activation energy, capture cross section, concentrations) of deep electron traps existing in the 4H-SiC layers and to indicate their possible origin.

2. Experiment

We studied 10 μm thick 4H-SiC epitaxial layers grown by CVD using Aixtron/Epigress VP508 horizontal hot-wall reactor on a 350 μm thick n^+-type 4H-SiC substrate with a net donor concentration of about 5×10^{18} cm^{-3}, purchased from SiCrystal AG. The *n*-type epitaxial layers were doped by nitrogen (N) with a donor concentration equal to about 1.5×10^{16} cm^{-3}. Afterwards, aluminum (Al) ion implantation was performed to form junction termination extension (JTE). Silicon dioxide (SiO_2) layer of a thickness of 1.1 μm was deposited by plasma enhanced CVD (PECVD) using Oxford Instruments Plasmalab 80 plus system as the implantation mask. A lithography process was used to define implantation windows in the shape of 40 μm wide rings around the Schottky contacts. JTEs were Al^+ implanted at 500 °C, with a total dose of 1.5×10^{13} ions/cm^{-2} and maximum ion energy of 220 keV. The ion energy and the dose were selected in order to provide a uniform dopants distribution in the implanted profile. Next, the SiO_2 mask was removed by a wet etching and a new SiO_2 mask was deposited again. The second ion implantation process was performed at 500 °C with Al^+ implanted at energy of 130 keV and dose of 1.8×10^{14} ions/cm^{-2} as well as at energy of 80 keV and dose of 4.7×10^{13} ions/cm^{-2}. It results in Junction Barrier Schottky (JBS) p^+ grid structure of 8 μm implanted strips separated by 5 μm spacings and 4 μm strips separated by 3 μm spacings in the area of the Schottky contacts, respectively. After a mask removal, the samples were annealed at 1600 °C for 20 min in argon (Ar) atmosphere to activate the dopants. A 150 nm thick titanium (Ti) layer was subsequently deposited on a backside of the wafer using magnetron sputtering. The layers were then annealed for 3 min at 1000 °C in Ar atmosphere and covered with 1 μm thick gold (Au) film in order to form final ohmic contacts. The Schottky contacts, with the area of 0.26 mm^2, were made by deposition of 200 nm thick nickel (Ni) on the epitaxial layer side by means of magnetron sputtering and annealing in Ar atmosphere at 350 °C for 5 min.

Electrical properties of the diodes were measured and analyzed by means of the measurement system composed of Keithley 2601A source-meter and Boonton 7200 capacitance bridge. The samples were mounted in a liquid nitrogen cryostat (Janis VPF-475), equipped with a temperature controller (Lakeshore 331). Conventional DLTS measurements were performed with the use of a specialized measuring software by recording and analyzing fast capacitance transients within 80–480 K temperature range for the reverse bias voltage equal to $U_R = -2$ V and a single filling pulse voltage $U_P = 0$ V. A width of filling pulses (t_p) was set to 1 ms. In order to obtain the important deep-level defect parameters, such as thermal activation energy (E_a) and apparent capture cross section (σ_a), different emission rate windows (e_n) in the range of 5–2000 s^{-1} were used.

3. Results and discussion

Fig. 1 shows the exemplary forward *J–U* characteristics of three similar 4H-SiC JBS diodes recorded at 300 K. All the studied samples exhibit comparable *J–U* characteristics with a single Schottky barrier behavior (i.e. no excess current is observed at low voltages). The diodes show also low reverse leakage current of about 0.2 nA at a reverse bias of −10 V. The average Schottky barrier height of 1.21 ± 0.05 eV, the ideality factor of 1.1 ± 0.1 and the series resistance of 63–73 Ω were extracted. The doping concentration of 4H-SiC epitaxial layers equal to about 1.65×10^{16} cm^{-3}, a value of the built-in potential of 1.0 ± 0.1 V and a barrier height of 1.2 ± 0.05 eV were also determined by means of *C–U* characteristics. On the basis of the obtained results we can conclude that 4H-SiC JBS diodes show excellent rectifying properties and thus are fully applicable for further studies of deep-level defects by means of space charge techniques, such as DLTS.

DLTS spectra measured with the reverse voltage (U_R) of −2 V, filling pulse voltage (U_P) of 0 V (i.e. filling pulse height was equal to 2 V) and filling pulse width (t_p) of 1 ms are shown in Fig. 2. The emission rate window of $e_n = 50$ s^{-1} was used. In the spectra, several positive peaks are visible at temperatures of about 93 K, 121 K, 156 K, 185 K, 247 K and 322 K for all studied diodes. In our system, a positive signal indicates that the revealed peaks are correlated with thermal emission of majority carriers from deep levels. According to this statement, we detected only deep electron traps in 4H-SiC JBS diodes, although we could also expected some minority hole traps introduced by implantation and post-implantation annealing processes [17]. It can follows from the fact that the implantation profile in the studied samples extends up to maximum of 300 nm under a surface, while in DLTS measurements, by applying voltage pulses from −2 V to 0 V, a probe region width is of about 350–550 nm, i.e. slightly below the implanted region.

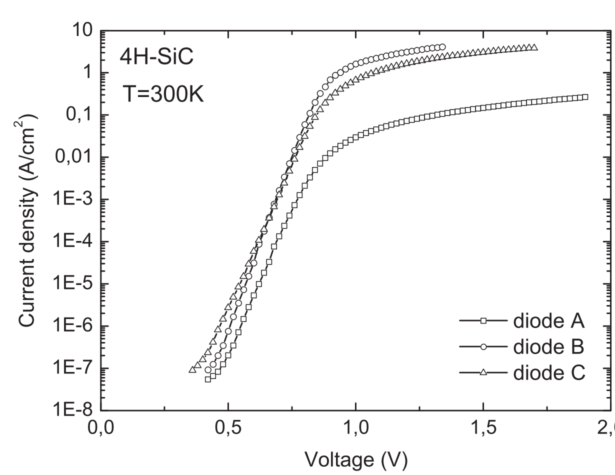

Fig. 1. Forward current density vs voltage (*J–U*) characteristics of 4H-SiC Junction Barrier Schottky (JBS) diodes recorded at 300 K.