Materials Science Forum
ISSN: 1662-9752, Vol. 1062, pp 523-527
doi:10.4028/p-92w3k6

Submitted: 2021-10-15
Revised: 2022-02-25
Accepted: 2022-03-17
Online: 2022-05-31

A Study of High Resistivity Semi-Insulating 4H-SiC Epilayers Formed via the Implantation of Germanium and Vanadium

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Keywords: 4H-SiC, Germanium, Vanadium, implantation, semi-insulating, high-resistivity, epitaxy

Abstract. A systematic germanium (Ge) and vanadium (V) study on 4H-SiC epitaxial layers is presented. Electrical results of TLM structures which were fabricated on these layers revealed that highly-doped Ge and V-implanted layers showed extremely low specific contact resistivity, down to 2×10^{-7} Ω.cm^2. Current flow in the conducting state of Schottky barrier diodes has been successfully suppressed in some implanted layers, with highly V doped samples showing current density values of approximately 1×10^{-5} Acm^{-2} at 10 V. DLTS spectra reveal the presence of germanium and vanadium centers in the respective samples as well as novel peaks which are likely related to the formation of a novel GeN center.

Introduction

The wide bandgap semiconductor 4H-silicon carbide (4H-SiC) has widely penetrated the power electronics device market over the past decade, utilising unipolar device structures such as Schottky barrier diodes and metal-oxide-semiconductor field-effect transistors (MOSFETs) with blocking voltage ratings from 600-3300 V. More recently, interest in high-resistivity, semi-insulating substrates for harsh environment applications has risen. This led to increased research activities in the development of localized semi-insulating layers via epitaxy or implantation in order to produce a SiC-on-insulator (SiCOI) materials system.

The use of a semi-insulating substrate reduces parasitic capacitance and leakage, and these are typically fabricated by adding dopants that act as electron-trapping recombination centers deep in the bandgap, at a concentration higher than the nominal dopants.

Applications for SiCOI include radiation hard electronics [1], GaN HEMT platforms [2], high power (> 1 kW) and high frequency (1 GHz) RF applications [3]. For 4H-SiC, the most common semi-insulating impurity is vanadium (V), which is often incorporated during substrate or epitaxial growth [4]. Recently, the introduction of germanium (Ge) has shown interest and yielded some potential benefits via epitaxy [5] or implantation [6] into SiC, with lower $Z_{1/2}$ levels [7], higher mobility [8] and higher conductivity[9]. However, less is known about the combination of Ge with additional n-type compensation doping. This would allow flexibility in device fabrication: allowing selective electrical enhancement or semi-insulation.

In this investigation, a matrix of Ge, V, and N co-implanted SiC epitaxial layers is characterized, both using electrical and physical methods, to demonstrate the change in insulating properties depending on implantation condition. Device structures that were fabricated on the layers include transfer length method (TLM) bars and Schottky barrier diodes (SBDs). The presence of deep levels in the material was investigated using deep-level transient spectroscopy (DLTS).

Experimental

10 µm thick, n-type doped (4 × 10^{15} cm^{-3}) epitaxial layers were grown on 100mm diameter, 4° off-axis, (0001) SiC wafers using an LPE ACiS M8 chemical vapour deposition (CVD) reactor. Growth was performed using tricholosilane (HCl_3Si) and ethylene(C_2H_4) at a C:Si ratio of 1.1 and Si:H_2 of 0.15% at a reduced pressure of 100 mbar. This gave a growth rate of 30 µm/hr using an effective flow of 0.12 sccm nitrogen (N_2) as a dopant. After an initial clean and dry etch to form mesas for the respective device structures, a 30 nm SiO_2 plasma deposition was performed at 200°C using bis(diethylamino)silane (BDEAS) and O_2 plasma precursors in an Ultratech Fiji G2 Plasma-Enhanced ALD system. Afterwards, quarter wafers underwent a blanket implantation schedule (box profile) that is outlined in Table 1. An additional high-dose n+ contact implant in patterned areas was performed where ohmic contacts were required (TLMs). Cross sections of the layer structure of SBD and TLM structures are shown in Fig. 1. 200 nm deep, box profile Ge and V implantations, were performed with high and low nominal concentrations of 5 × 10^{18} cm^{-3} and 5 × 10^{16} cm^{-3}, both values exceeding the as-grown doping concentration by at least one order of magnitude. Samples were then laser cut into 10 × 10 mm chips before being cleaned and given post-implantation anneal at 1600°C. Ti/Ni (30/100 nm) backside contacts (and topside for TLM samples) were then deposited, before annealing the samples at 1000°C for 2 minutes to form ohmic contacts. Finally, 100 nm thick molybdenum (Mo) was e-beam deposited, before being annealed at 500°C for 2 minutes in argon (Ar) ambient to form Schottky contacts.

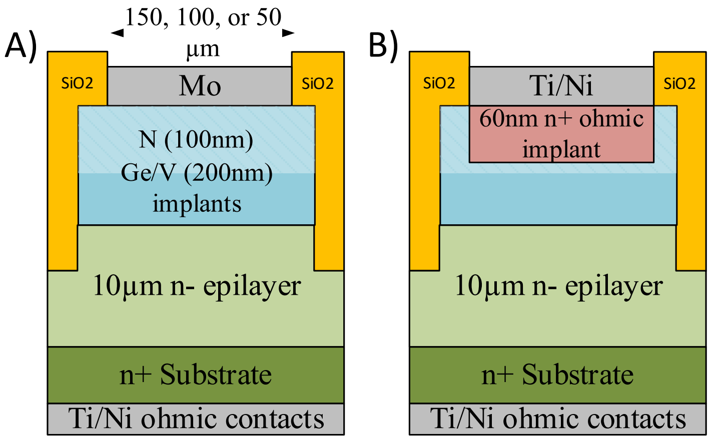

Figure 1: General schematic for implantation and device layout, a) specifically for a SBD, b) ohmic contact formation for TLM measurement.

Table 1: Overview of the implantation schedule and specific contact resistivity and sheet resistance values for all samples, with post-implantation anneal at 1600°C.

#ID	Sample description	Implanted concentration (cm^{-3})	Implanted thickness (nm)	Sheet resistance (Ω.sq^{-1})	Specific contact resistivity (Ω.cm^2)
S1	Lowly doped Ge	Ge: 5 × 10^{16}	Ge: 200	2.06	3.90 × 10^{-2}
S2	Lowly doped Ge with co-doped N	N: 1 × 10^{18} Ge: 5 × 10^{16}	N: 100 Ge: 200	15.66	1.51 × 10^{-2}
S3	Highly doped Ge	Ge: 5 × 10^{18}	Ge: 200	10905	1.03 × 10^{-3}
S4	Highly doped Ge with co-doped N	N: 1 × 10^{18} Ge: 5 × 10^{18}	N: 100 Ge: 200	8165	2.19 × 10^{-7}
S5	Control (blanket n+)	N: 5 × 10^{18}	N: 200	13.95	8.38 × 10^{-3}
S6	Lowly doped V	V: 5 × 10^{16}	V: 200	1016	5.85 × 10^{-4}
S7	Lowly doped V with co-doped N	N: 1 × 10^{18} V: 5 × 10^{16}	N:100 V: 200	79.74	3.49 × 10^{-3}
S8	Highly doped V	V: 5 × 10^{18}	V: 200	12233	3.48 × 10^{-3}
S9	Highly doped V with co-doped N	N: 1 × 10^{18} V: 5 × 10^{18}	N: 100 V: 200	9231	1.52 × 10^{-5}

DLTS measurements were carried out using a PhysTech FT-1230 DLTS system. For sample preparation, an additional 100 nm layer of nickel was added to the Schottky contacts, the samples were glued to a chip carrier using conductive EPO-TEK®P1011 and wire bonded. The displayed data is for a time window of 64.5ms, a reverse bias of -1 V, a pulse voltage of 0 V and a filling pulse duration of 10 ms. In addition to the implanted samples, a control sample with no implantations was also analysed.

Results

Room temperature current-voltage (I-V) sweep measurements were taken on TLM structures from -1 to 1 V (1000 steps) to investigate the impact of Ge and V on the specific contact resistivity and sheet resistance. An overview of the results of these TLM measurements is also shown in Table 1. This emphases the drastic increase in sheet resistance from 13.95 $\Omega.sq^{-1}$ in the nitrogen-blanket implanted sample (sample 5) to sheet resistance values up to around 10000 $\Omega.sq^{-1}$ for the samples with high semi-insulating doping, both with and without N co-doping (S3,S4,S8 and S9). Hence, the high-dose implantation of Ge and V leads to a decrease in specific contact resistivity up to 2.19×10^{-7} $\Omega.cm^2$ for a highly co-doped Ge sample (S4), which is a promising result allowing a low contact resistance in conjunction with semi-insulating properties.

In a next step, the rectifying characteristics of Schottky diodes were auto-probed at room temperature using a Keysight B1505A with a Semiprobe semi-automatic probe station. On-state current densities were extracted for at least 25 devices. Fig. 2 (a) depicts the forward bias response of devices from the different samples. Here, the V-implanted samples without co-doping (S6&8, blue and green straight line) show a decrease in leakage current density, with current values not exceeding 1×10^{-1} $A.cm^{-2}$ and 1×10^{-5} $A.cm^{-2}$ at a forward bias of 10V, respectively. A distinction can be seen when comparing this to Ge-implanted samples without co-doping (S1&3, wine and purple solid traces), which exceeded much higher current density values of 1×10^{1} $A.cm^{-2}$ at the same voltage. Although the specific contact resistivity is reduced by highly doping SiC epilayers with Ge and V, only the highly-doped vanadium samples appear to significantly reduce the specific on-resistance in the forward conducting state.

DLTS temperature scans from a selection of samples is shown in Fig. 2 (b) and an outline of the observed defect levels is given in Table 2. In addition to the intrinsic $Z_{1/2}$ level and the adventitious Ti level, the implantation of semi-insulating dopants has introduced several levels. Peak #5, observed at ~480 K in sample 6 [10], is typical of V in 4H-SiC, and the similar level at ~430 K in samples 8 & 9 is probably also due to V, possibly with a shift in ΔE caused by the high implantation dose. Similarly, peak #3 observed at ~240 K in samples 1 & 2 is likely a level induced by Ge in 4H-SiC. Peaks #2 and #6 are not characteristic of Ge in 4H-SiC and are only observed for a high Ge dose, co-doped with N, suggesting that a new defect is formed for Ge and N co-implantation. This is consistent with the extremely high DLTS signal from peak #6.

Table 2: Overview of the detected DLTS peaks and their probable identity.

#Id	Approx. peak temperature (K)	Observed for	Probable identity	Reference
1	90	All	Ti	[10]
2	190	High Ge doping	Unknown, possible GeN centre	-
3	240	All Ge	Ge	[11]
4	310	All except V doped	$Z_{1/2}$	[10]
5	430/480	All V	V	[10]
6	510	High Ge w. co-doping	Unknown, possible GeN centre	-

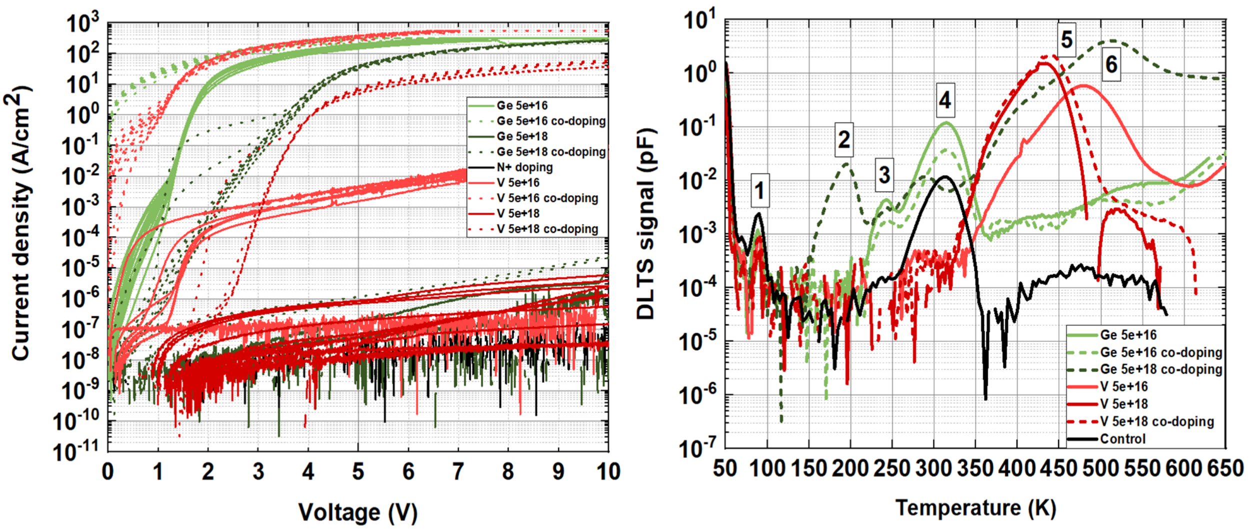

Figure 2: (a) Typical on-state I-V of the Schottky diodes, measured at 22°C. (b) DLTS spectrum of Ge and V implanted SBDs, measured from 50 K to 650 K, with t_w = 64.5 ms. The numbered items refer to the peak identifiers in Table 2.

Conclusion

Highly implanted Ge and V layers significantly decrease specific contact resistivity values of TLM structures, down to 2.19 x 10^{-7} $\Omega.cm^2$ for a high dose Ge sample (sample 4), which is a promising result regarding the semi-insulating properties. In the conducting state of Schottky barriers, only the highly-doped V layers showed a significant reduction of current density levels to 1 x 10^{-5} $A.cm^2$ at 10 V bias. DLTS spectra reveal, beside the presence of common $Z_{1/2}$ and Ti peak, Ge and V peaks in the respective samples. In addition, novel peaks are observed which are thought to be related to the presence of GeN.

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