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Magnetic, optical and electrical characterization of SiC doped with scandium during the PVT growth

K. Racka [a,*], A. Avdonin [b], M. Sochacki [c], E. Tymicki [a], K. Grasza [a,b], R. Jakieła [a,b], B. Surma [a], W. Dobrowolski [b]

[a] Institute of Electronic Materials Technology,133 Wólczyńska Street, 01-919 Warsaw, Poland
[b] Institute of Physics, Polish Academy of Sciences, Aleja Lotników 32/46, 02-668 Warsaw, Poland
[c] Institute of Microelectronics and Optoelectronics of Warsaw University of Technology, 75 Koszykowa Street, 00-662 Warsaw, Poland

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ABSTRACT

Scandium is introduced into bulk SiC during the physical vapor transport (PVT) growth. SiC crystals grown with different Sc contents (from 0.5 wt% up to 2.5 wt%, added to the SiC source material) are studied. Magnetic properties of SiC doped with scandium during the PVT growth are reported for the first time. The presence of antiferromagnetic interactions between magnetic moments of Sc ions is concluded from the temperature dependence of magnetic susceptibility. Detailed PL spectra of 4H-/6H-SiC:B and 4H-/6H-SiC:Sc crystals are presented. A new energy level of 35–37 meV is found on SiC:Sc samples and its possible assignment to a complex defect, consisting of nitrogen donor and scandium acceptor, is proposed.

1. Introduction

Silicon carbide (SiC) is a wide bandgap semiconductor (e.g. 3.24 eV for the 4H polytype) with unique properties, such as high electric breakdown field, high thermal conductivity and extreme thermal stability. Thus it is an attractive semiconductor material for advanced applications, high-temperature, high-frequency and high-power devices. Due to its unique properties, SiC has been considered in the past few years as a candidate for dilute magnetic semiconductors (DMSs), next to widely studied III–V or II–VI semiconductors, such as: InAs, GaAs, GaN and ZnO ([1,2] and references therein). DMSs with magnetic phase transition above room temperature are considered as promising candidates for spintronic applications. In devices using DMS compounds, the use of spin for storage and processing of information creates a hope to obtain a new class of semiconductor memories, as well as signal processing or light emitting devices. In practice, it corresponds to the desire of fabrication of the next-generation lasers, magnetic sensors, spin transistors and spin processors utilizing the spin phenomena occurring in DMSs.

DMS compounds must be a semiconductor solid solution, in which magnetic dopants are substituted for a few percent of host elements, and not a matrix with embedded transition metal clusters, precipitates or inclusions of secondary crystalline phases that are responsible for the observed magnetic properties (structural defects can be also involved, e.g. the coeffect of magnetic elements doping along with the native defects may also play a role for the ferromagnetic order) [3,4]. A homogeneous „true" DMS material with above room-temperature phase transition has not been yet discovered. Hence, it seems that a search for a DMS material doped with magnetic ions distributed in its volume is justified. Such a potential candidate for the DMS appears to be SiC grown in the presence of magnetic elements by the physical vapor transport (PVT) method. One of the advantages of the growth of SiC by the PVT method is a possibility to produce the crystals in which a magnetic dopant is distributed over the whole bulk, and not only in a narrow range of material, as it is in the case of the ion implantation method. Moreover, the PVT growth does not introduce damaged regions and other lattice defects, which are often encountered in SiC samples as the consequence of a direct ion implantation process [5].

The interest for incorporation of magnetic ions into SiC to produce ferromagnetism, and thus a potential candidate for spintronics applications is displayed in the literature [1–11]. Due to difficulty of doping of SiC by thermal diffusion, in many reports the ion implantation is used as a method of introducing of transition metal

* Corresponding author. Tel.: +48 22 835 30 41x62174; fax: +48 22 864 54 96.
E-mail address: Katarzyna.Racka@itme.edu.pl (K. Racka).

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[2,5,6,11,12] or rare earth [13,14] impurities into SiC. Up to now, magnetic properties of transition metals in SiC, such as: Cr, Fe, Mn, Co and Ni [1–11] have been investigated and the ferromagnetism with a high magnetic phase transition temperature (~270 K) was reported for the Fe-implanted SiC [2]. But the origin of the ferromagnetic contributions in implanted SiC is still to be determined. Recently, magnetic characterization of Mn-doped SiC films, deposited on Si substrates by RF-magnetron sputtering technique by An et al. [3] has shown that the films were ferromagnetic with magnetic phase transition temperature of above 300 K. The authors speculated that the ferromagnetism of the films was intrinsic and relies on the percolation of bound magnetic polarons.

The aim of this work was to grow bulk SiC crystals doped with scandium, which is another transition metal element, during the growth by the PVT method. The main purpose of our research was to check if the Sc-doping of SiC crystals by the PVT is a possible approach for fabrication of the DMS material. In this work, magnetic properties of SiC:Sc have been reported for the first time, as such data previously did not exist in the literature. Optical and electrical properties of the obtained SiC:Sc crystals have been also investigated. Experimental results presented in this paper can extend sporadic information on such properties existing in the literature. There are few reports on scandium doping of SiC (e.g. [15–19]). The most detailed investigations on optical and electrical properties of SiC:Sc are presented in paper by Tairov et al. [15] where the crystals were subjected to examination of Hall effect, electric conductivity and of photoluminescence. The other papers [16–19] mostly concentrate on the microscopic structure of the Sc impurity in SiC, i.e. the knowledge how Sc is incorporated into the SiC lattice. It is gained from studies of electron paramagnetic resonance (EPR) [16–18] or electron paramagnetic resonance detected via the photoluminescence (PL-EPR) [19].

2. Experimental

SiC crystals were grown by the PVT method on the C-face of on-axis 6H-SiC crystal seeds and in the presence of different Sc impurity contents (0.5 wt%, 1 wt% and 2.5 wt%) added to SiC source material. As the source of scandium, the commercial granules of metallic scandium were used. They were introduced into a small graphite container, which was placed inside the SiC source. A narrow channel in the container lid made possible a gradual vaporization of scandium during the SiC crystal growth. The increase of the amount (wt%) of Sc dopant in the SiC source material does not necessarily lead to a higher Sc content in the grown crystal due to saturation of the growth atmosphere with scandium. As scandium was present in the growth atmosphere during the whole growth process, there are not expected differences in the distribution of Sc dopant at various stages of the crystal growth.

Magnetic properties of SiC crystals doped with Sc were measured in LakeShore 7000 Series susceptometer/magnetometer, while their structural properties were examined by X-ray diffraction (XRD), X-ray photoemission spectroscopy (XPS), photoluminescence measurements (PL), optical absorption and secondary ion mass spectroscopy (SIMS).

Electrical properties of SiC:Sc were studied by measurements of the van der Pauw resistivity and the Hall effect as functions of the temperature. Measurements were carried out on square samples 5×5 mm^2 with thickness of 0.5–0.9 mm. Electrical contacts were made by vacuum deposition of Ni contact pads on the corners of the samples. The electrical connection to pads was made with a silver conducting paste.

The reference SiC crystal, grown on the C-face of the 6H-SiC crystal seed without scandium additive and with the same growth parameters, was also studied. Moreover, a sample of 6H-SiC unintentionally doped with nitrogen to a concentration of 10^{18} cm^{-3}, which was cut from the reference SiC crystal, and implanted at $T=500$ °C with 270 keV Sc ions (with a dose of 4×10^{15} cm^{-2}) was also investigated. The implanted sample was then annealed in argon atmosphere at 1500 °C (30 min) in order to remove the lattice damage inherent to the ion implantation.

SiC crystals doped with Sc, investigated in this work, were grown without intentional nitrogen and boron doping. The main source of nitrogen impurity in these crystals was the SiC source material. We also present the results of PL measurements for our other SiC crystals doped with boron during the PVT-growth in order to show a difference between boron-related and scandium-related photoluminescence in 4H- and 6H-SiC.

3. Results and discussion

3.1. Structural and optical properties of SiC:Sc

SiC crystals, grown on the C-face of on-axis 6H-SiC seeds with addition of scandium (0.5 wt% Sc, 1 wt% Sc and 2.5 wt% Sc) to SiC source material, consisted of a mixture of 4H-, 15 R- and 6H-SiC polytypes (Fig. 1a). The undoped SiC reference crystal (0 wt% Sc)

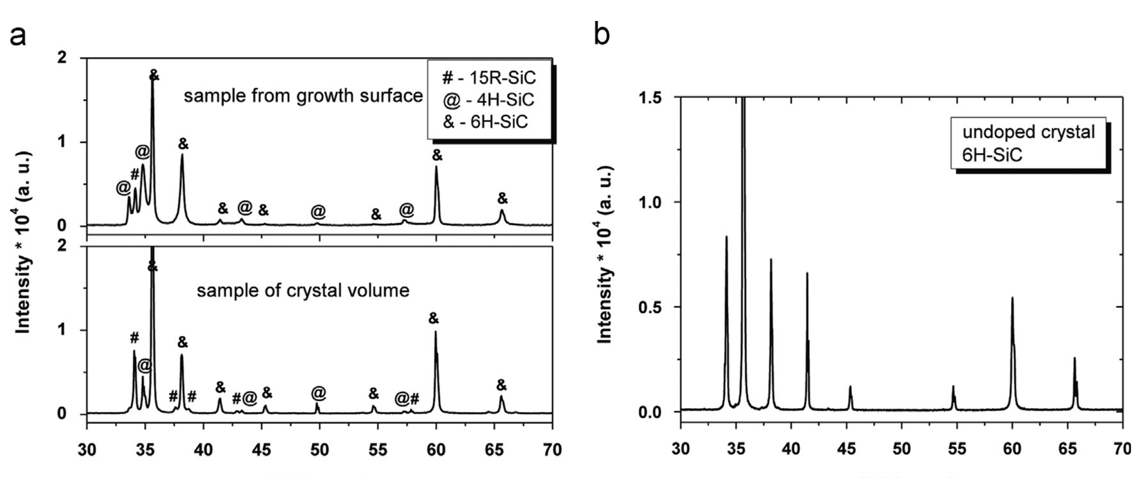

Fig. 1. XRD spectra measured for: (a) samples cut from growth surface and from volume of the SiC crystal grown with 2.5 wt% scandium addition to the SiC source material (diffraction peaks characteristic of scandium oxides or Sc metallic inclusions are not visible), and (b) undoped SiC crystal.