Radiation Physics and Chemistry 127 (2016) 169–176

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

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

Structural and defects induced phenomena in γ-rays irradiated 6H-SiC

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HIGHLIGHTS

- No formation of others SiC polytypes.
- The gamma rays irradiation has induced a slight surface amorphization.
- A re-crystallization at lower and higher doses is noticed.
- Larger doses induced a substantial internal stress.

ARTICLE INFO

Article history:
Received 7 March 2016
Received in revised form
9 June 2016
Accepted 18 June 2016
Available online 25 June 2016

Keywords:
SiC
γ-Rays
Defects
Nuclear materials
Radiations

ABSTRACT

Damages and/or defects induced by γ-rays irradiation on 6H-SiC single crystals in channeled configuration towards ⟨006⟩/⟨0012⟩ crystallographic directions are reported in the range of 0–1200 kGy. Atomic force microscopy, X-rays diffraction, Raman and photoluminescence investigations were used to obtain a comprehensive set of informations on the nature and population distribution of the induced defects. Primarily, there was no carbon clusterization upon γ-rays irradiation and hence no formation of others SiC polytypes. In contrast, the γ-rays irradiation has induced an increase of the surface roughness at higher doses, which indicates a structural degradation. Larger doses induced an emergence of deeper shallow traps at energies greater than 350 meV below the bandgap.

1. Introduction

Several reactor systems have been proposed and some of these have been developed to prototype and to full commercial scale (Rhodes and Beller, 2000; British Petroleum Statistical Review of World Energy, 2009). Six types of reactors namely: Magnox (Magnesium Non Oxidizing) reactor type, AGR (Advanced Gas-Cooled Reactor), PWR (Pressurized Water Reactor), BWR (Boiling Water Reactors), CANDU (Canadian Deuterium-Uranium) and RBMK (Reaktor Bolshoy Boshchnosti Kanalniy) have emerged as potential designs used to produce commercial electricity around the world. A further reactor type, the so-called Pebble Bed Modular Reactor (PBMR) has been studied since early 1990s (South African National Department of Energy: Integrated Resource Plan, 2010). The concept of the PBMR, goes back to the 1950s through the idea of Helium cooled high temperature reactor pioneered by R. Schulten (South African National Department of Energy: Integrated Resource Plan, 2010). This concept was first employed successfully in the 15 MWe (40 MWth) AVR (Arbeitsgemeinschaft Versuchsreaktor) research reactor in Zürich, which started up in 1966 and shut down in 1988 following the Chernobyl accident. The fuel of such a system consists of coated uranium dioxide (UO_2) particles compacted into tennis-ball-sized graphite spheres: the pebbles. The UO_2 particles coatings include silicon carbon (SiC) and pyrolitic carbon, which are capable of maintaining integrity at very high temperatures. More precisely, the PBMR fuel particle consists of low enriched uranium triple-coated isotropic (TRISO) particles contained in a molded graphite sphere as illustrated in

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http://dx.doi.org/10.1016/j.radphyschem.2016.06.018
0969-806X/

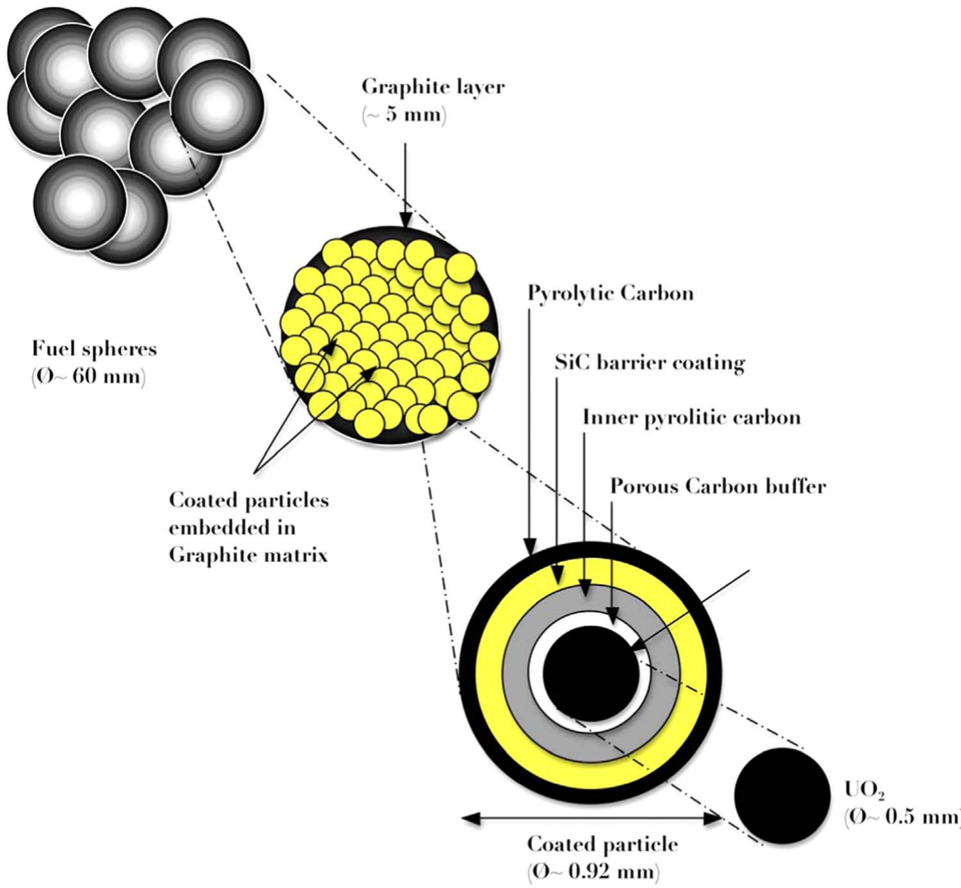

Fig. 1. Schematic configuration of a PBMR fuel element.

Fig. 1. The coated particle consists of a kernel of UO_2 surrounded by four coating layers. The first layer deposited on the kernel is a porous carbon, followed by an inner layer of dense pyrolitic carbon (IPyC), a SiC layer and finally the outer layer of pyrolitic carbon (Ref. Fig. 1). The porous carbon accommodates any mechanical deformation that may arise from the UO_2 kernel during the lifetime of the fuel as well as gaseous fission products diffusing out of the kernel. The SiC coating layer provides the mechanical strength and acts as a barrier to the diffusion of any fission products. The last outer pyrolitic carbon layer coating protects the SiC coating mechanically.

SiC allows operability at extreme conditions of temperature and pressure (Nava et al., 2008; Mandal et al., 2011b; Ruddy et al., 2006; Bertuccio et al., 2001; Sellin and Vaitkus, 2006a; Kern, 1970; Markwitz et al., 2004). It is regarded as a strong candidate for high-power, high-frequency, and high-temperature devices due to its excellent physical properties, that is, a wide band gap ensuring a very low leakage current, excellent chemical properties, high thermal conductivity, high saturation velocity of carriers and high breakdown field as well as it significant high radiation tolerance (Ohshima et al., 2003; Nava et al., 2004, 2003; Kinoshita et al., 2005; Sellin and Vaitkus, 2006; Cunningham et al., 2002). As such and in nuclear applications, radiation hardness, in particular, is a very important factor for the SiC based detector systems used in experiments of high energy physics, like those done by the super Large Hadron Collider (LHC) (Bruzzi et al., 2005). For example, the inner tracker detectors in super LHC needed to survive fast-hadron fluencies of above $10^{16}/cm^2$. The community of high-energy physics is exploring novel detector materials and technologies that will allow devices to operate up to this limit. For instance, Nava et al. (2003) have developed the 4H-SiC particles detector for minimum ionizing particles and alpha particles. They have demonstrated its performance and the capability of SiC operating under high radiation environments. On the other hand, SiC has also been considered for realizing dosimeters and spectrometers for the detection of neutrons, γ-rays, and soft X-rays produced in nuclear reactors and/or by radiotherapy (Bertuccio and Casiraghi, 2003; Dulloo et al., 1999). Due to the hostile environment created in the reactors operation specifically, some of the singular SiC properties are compromised. The success of the application of this material in nuclear environments such as the PBMR specifically is reliant on the integrity of SiC and requires a good knowledge of all the effect of different types of radiations on its physical properties. Low fluence irradiation of SiC is known to produce point defects, such as vacancies and interstitials, or point like defects. The effect of radiations on bulk and nanostructured coatings of SiC has been investigated by various experimental techniques and computer simulations for about two decades (Terry et al., 2011; Mandal et al., 2012; Ohshima et al., 2003; Nava et al., 2004; Kinoshita et al., 2005; Sellin and Vaitkus, 2006; Cunningham et al., 2002; Bruzzi et al., 2005; Bertuccio and Casiraghi, 2003; Dulloo et al., 1999), there is still a need for a minimization of the defect creation and migration processes particularly formed after high radiation doses of γ-rays in specific crystalline directions such as the one considered in this contribution; [006]/[0012]. In this regard, one should single out the investigations reported in the literature by Lee et al. (2003), Metzger et al. (2002) and the most recent one by Mandal et al. (2013) as the major γ□-irradiations in the literature were carried out within ⟨1120⟩ direction or in random configurations.

As it was mentioned above, the study of γ-rays induced defects (from low damage level to full amorphization) is a topic that has