Current-voltage characteristics of neutron irradiated nanocrystalline silicon carbide (3C−SiC)

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ABSTRACT

At the present work, nanocrystalline silicon carbide (3C−SiC) irradiated by neutrons (2×10^{13} n/cm²s) up to 20 h. The current–voltage (I−V) characteristics of the nanocrystalline 3C−SiC particles have been investigated in the voltage range of −100 V to + 100 V with a 5 V step. The slope of the line changed at the I−V characteristic of the nanomaterial after neutron irradiation. Simultaneously, the resistance of nanocrystalline 3C−SiC decreased approximately from 4 MΩ to 1 MΩ after neutron irradiation. Moreover, the Fowler-Nordheim plots showed that the processes occurred in the nanomaterial were directly based on a tunnel effect and no field emission was observed. It is clear from Fowler-Nordheim plots that, thermal activity is dominated at the all experimental intervals.

1. Introduction

Over the past decade, silicon carbide and its various composites have been widely studied by the researchers in the world [1–14]. SiC with attractive physical and chemical resistance has a wide range of applications in extrinsic environments [15–19]. The change of the bandwidth in the 2.2 eV–3.2 eV ranges has led to a wide use of SiC as a semiconductor in electronic systems [20–27]. In the general approach, SiC is a covalently bonded semiconductor. In terms of structure, each Si atom is covalently bonded to four carbon atoms and vice versa. Si and C atoms in SiC have combined in different modifications and have led to the formation of more than 200 polytypes. The most common of these are cubic (3C−SiC) and hexagonal (4H−SiC and 6H−SiC) polytypes. In this study, nanocrystalline 3C−SiC were used, in which the bandgaps was 2.2 eV at room temperature.

Neutron transmutation is one of the most effective methods for the making of doping elements in the nanomaterials. Several effects of neutron irradiation on the 3C−SiC nanocrystals have been investigated at the various scientific studies [28–35]. It is easy to place the doping elements in the atomic lattice of the nanomaterial with the neutron flux. It is clear, newly occurred doping elements will cause the change in the physical properties of the nanomaterial. One of the most common methods for studying physical properties and electronic processes is the I−V characteristic [36–40]. In the general approach, the I−V characteristic of silicon carbide has been widely studied at the various scientific papers [38–43]. However, the I−V characteristic of silicon carbide has been studied less in nano dimensions. Furthermore, neutron irradiation effect on the I−V characteristic, current - resistance, voltage - resistance, and Fowler-Nordheim dependencies have almost not been studied. At the present work, the changes in the physical properties of nanocrystalline 3C−SiC as a result of neutron irradiation have been studied by the I−V characteristic. Moreover, the current-resistance, voltage - resistance, Fowler-Nordheim, voltage -power and specific power-current density dependencies were comparatively analyzed before and after neutron irradiation.

2. Experimental

At the present work, research object is silicon carbide nanoparticles, which have the special surface area (SSA) of 120 m²/g, the particle size of 18 nm and the density of 0.03 g/cm³ (true density 3.216 g/cm³) (US Research Nanomaterials, Inc., TX, USA). Samples irradiated by neutron flux (2×10^{13} n/cm²s) in the central channel (channel A1) of the TRIGA Mark II light water pool-type research reactor at full power (250 kVt) in the Reactor Center of Institute Jozef Stefan (IJS) in Ljubljana, Slovenia. It is important to note that, if the reactor is working at full power then neutron flux parameter as followed: 5.107×10^{12} n/cm²s (1 ± 0.0008, E_n < 625eV) for thermal neutrons, 6.502×10^{12} n/cm²s (1 ± 0.0008, E_n ~ 625eV ÷ 0.1 MeV) for epithermal neutrons, 7.585×10^{12} n/cm²s (1 ± 0.0007, E_n > 0.1 MeV) for fast neutrons and finally, the flux is 1.920×10^{13} n/cm²s (1 ± 0.0005) for all neutrons in the central channel [44–51].

3C−SiC nanoparticles have been pressed at press machine (3 kN cm^{-2}) with 2.2 mm height and 15 mm diameter. Prepared samples placed in an aluminum container corresponding to the reactor channel at "Thin Films and Surfaces Physics" Laboratory of IJS. Nanocrystalline 3C−SiC were continuously irradiated in the central channel for 1, 5, 10 and 20 h. The activity of the samples increased up to 3GBq after the neutron irradiation [30]. Therefore, all measurements were carried out approximately 500 h after the neutron irradiation. The silver contacts were put on the surface of the samples in a special condition and their quality was checked (Ogussa, Leitsilber 200). Then, the I−V characteristics of the samples were measured in the "Keithley 238 High Current Source Measurement Unit" at the "Photovoltaics and Optoelectronics Laboratory" of University of Ljubljana. All experiments were conducted at room temperature in the voltage range of −100 V to +100 V and by 5 V steps. Hysteresis measurement was performed (voltage from −100 V to 100 V and vice versa). Bottom side was placed onto the copper plate while the top side was contacted with a contact tip. Each sample was measured on three times where the position of the contact tip was changed. The device was managed by the LabView software and the results corresponding to the obtained values were graphically described in the "OriginPro 9.0" program.

3. Results and discussion

The I−V characteristics of the nanocrystalline 3C−SiC were measured voltage range of −100 V ÷ +100 V at room temperature. The experiments revealed that there were differences in dependence of I−V, P - U, etc. before and after neutron radiation. The I−V characteristic of nanocrystalline 3C−SiC before and after neutron radiation has been described at Fig. 1.

The linear plot at the I−V characteristic and small angle slope corresponding to voltage axis, described relatively high resistance before neutron irradiation. Simultaneously, plot symmetry corresponding to the zero points of voltage and current axis indicates that the samples are sufficiently clean [39]. Moreover, there is a steepness (slope) of the line changed at the I−V characteristic of the nanocrystalline 3C−SiC after neutron irradiation. In this way, after neutron irradiation, the plots angle with the voltage axis sharply increased in the I−V characteristic of the nanocrystalline 3C−SiC. On the other hand, it is known that the cotangent of this angle directly characterizes the resistance of the sample: cotα = R. An increased the angle formed by the plots and the voltage axis after the neutron irradiation causes a decrease the resistance of the sample. Thus, the electrical conductivity of the samples increases after neutron irradiation, which has been proven in other experiments [32,35]. Like previous experiments, this increase can be

Fig. 1. I–V characteristics of the nanocrystalline 3C−SiC before (c.s.) and after (1 h, 5 h, 10 h, and 20 h) neutron irradiation.

explained by the neutron transformation, dangling bonds, formation of defects, or charge carriers [28–35]. The shifting curves also become in current - resistance and voltage - resistance plots after neutron irradiation (Fig. 2).

As can be seen from Fig. 2, the resistance of nanocrystalline 3C−SiC is sharply reduced after neutron irradiation. At the same time, in Fig. 2a, a shifting occurs in the current-resistance plots in the direction of resistance with respect to the current axis. It is possible the amount of the current passing through this environment increases after the neutron radiation according to the curve shifts. As can be seen from Fig. 2b, the value of positive and negative voltage almost does not affect the resistance of the sample. However, there is a sharp decrease in resistance of nanocrystalline 3C−SiC after neutron irradiation. It should be noted that the resistance partly decreases before neutron irradiation due to the voltage increasing (Fig. 2b). Simultaneously, the value of the resistance after neutron irradiation does not depend on voltage. The Fowler-Nordheim plots were compared before and after neutron irradiation for the investigated of direct tunneling or field emission of nanocrystalline 3C−SiC (Fig. 3).

Simply, tunnel barrier at the molecular level is characterized by Simmons's approach in the I−V dependencies [52–55]:

$$I = \frac{qA}{4\pi^2\hbar d^2}\left[\left(\varphi - \frac{qV}{2}\right)\exp\left(-\frac{2d\sqrt{2m^*}}{\hbar}\sqrt{\varphi - \frac{qV}{2}}\right)\right.$$
$$\left. - \left(\varphi + \frac{qV}{2}\right)\exp\left(-\frac{2d\sqrt{2m^*}}{\hbar}\sqrt{\varphi + \frac{qV}{2}}\right)\right] \tag{1}$$

here, A is the junction area, d is the barrier width, m^* is the effective mass of the charge carrier, φ is the barrier height, $\hbar$ is the reduced Planck's constant and q is the electron charge. The tunneling probability of the process depends on the shape of the barrier of the chosen sample in the Fowler-Nordheim plots [55]. In limiting case, if we take a barrier as a rectangular, the I−V dependencies is directly explained by the tunnel effect [52–55]:

$$I \propto V \exp\left(-\frac{2d\sqrt{2m^*\varphi}}{\hbar}\right) \tag{2}$$

On the other hand, if the applied voltage exceeds the barrier height, the barrier turns into a triangular form from a rectangular shape and this triangular deformation causes the formation of the Fowler-Nordheim tunnel (field emission) [52–55]. In this case, I−V dependence can be characterized by the equation below:

$$I \propto V^2 \exp\left(-\frac{4d\sqrt{2m^*\varphi^3}}{3\hbar qV}\right) \tag{3}$$

Fowler-Nordheim plots explain directly whether the process is a tunnel or field emission. In this case, Eqs. (2) and (3) can be expressed as follows [52–55]:

$$\ln\left(\frac{I}{V^2}\right) \propto \ln\left(\frac{1}{V}\right) - \frac{2d\sqrt{2m^*\varphi}}{\hbar} \tag{4}$$

$$\ln\left(\frac{I}{V^2}\right) \propto -\left(\frac{1}{V}\right)\frac{4d\sqrt{2m^*\varphi^3}}{3\hbar q} \tag{5}$$

It should be noted that if Fowler-Nordheim's plots are logarithmic, the process is explained by the direct tunneling and if it is a negative slope line, the process can be explained by field emission [54,55]. Existing ln(A/V^2) vs. 1/V plots in Fig. 3 corresponds to Eq. (2) which is can distinctly show the direct tunneling [52–55]. The Fowler-Nordheim plots in Fig. 3 shows that the process is directly based on the tunnel effect in nanocrystalline 3C−SiC at the temperature at which experiments are carried out, and no field emission is observed. The curves observed in Fig. 3 show that thermal activity before and after neutron irradiation in the nanocrysta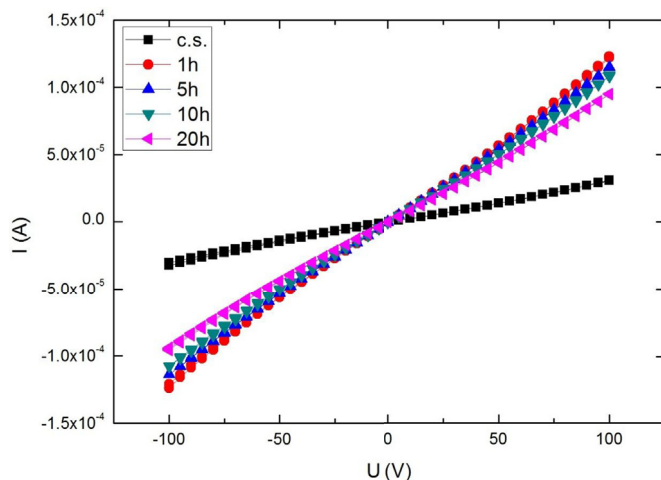lline 3C−SiC is dominant at all intervals