Nuclear Instruments and Methods in Physics Research A 622 (2010) 200–206

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

The effects of neutron irradiation and low temperature annealing on the electrical properties of highly doped 4H silicon carbide

Ekrem Almaz [a,*], Stephen Stone [b], Thomas E. Blue [b], Joseph P. Heremans [b]

[a] Alparslan University, Science and Arts Faculty, Physics Department, İstasyon cd., 49100 Muş, Turkey
[b] Nuclear Engineering Program, The Ohio State University, 201 West, 19th Avenue, Columbus, OH 43210-1189, USA

ARTICLE INFO

Article history:
Received 26 March 2010
Received in revised form
15 June 2010
Accepted 16 June 2010
Available online 14 July 2010

Keywords:
Neutron irradiation
Silicon carbide
Hall effects
Annealing

ABSTRACT

The effects of neutron irradiation on the electrical properties of highly doped 4H SiC were studied. The material was fabricated into standard Hall bars for characterization of the material's resistivity, free-carrier concentration and electron Hall mobility as a function of 1 MeV equivalent neutron fluence in SiC ($\Phi^{Eq}_{1\,\mathrm{MeV,SiC}}$). The post-irradiation effects of low temperature (175 °C) annealing on the same properties were also investigated. It was found that: (1) the material's resistivity doubled for $\Phi^{Eq}_{1\,\mathrm{MeV,SiC}} = 2.7\times10^{16}$ cm^{-2}, (2) the resistivity recovered (i.e. decreased) by only 8±1% from its post-irradiation values after 2 h of annealing, (3) the carrier concentration decreased linearly with $\Phi^{Eq}_{1\,\mathrm{MeV,SiC}}$ with a carrier removal rate of ~48.5±6.3 cm^{-1}, (4) within experimental uncertainty, the carrier concentration recovered to its pre-irradiation values after 2 h of annealing, (5) the Hall mobility decreased linearly with $\Phi^{Eq}_{1\,\mathrm{MeV,SiC}}$ with a mobility damage constant of (1.49±0.2)10^{-19} V s and (6) the Hall mobility was further degraded (i.e. decreased) by annealing. The mobility was found to decrease from its post-irradiation value by 27±8% after 2 h of annealing.

1. Introduction

Silicon carbide is one of the most promising wide band gap semiconductors available today. It has electrical and mechanical properties that make it desirable for use in high power, fast switching systems. Furthermore, some of these same properties make it appropriate for use in harsh environments, with intense radiation fields, and/or high temperatures. Space bound devices will encounter high ionizing radiation in the form of gamma-rays, heavy-charged particles, light-charged particles, especially protons, and energetic electrons and may be required to operate at high temperatures due to limited capability for thermal heat rejection. Devices for use in Gen IV reactor applications may encounter fast neutron, thermal neutron, high energy gamma-ray and beta radiation and may also be exposed to high temperatures. In comparison to other semiconductor materials, SiC has properties that are ideal to meet the needs of these various operating conditions. In order to be able to better design SiC devices for these applications, it is important to understand how the electrical properties of this material change under irradiation [1,2].

The goal of this study is to better understand how the electrical properties of a major component in power devices, the bulk substrate, change as a function of neutron damage. Also of interest is how this damage can be either mitigated or repaired by operation at slightly elevated temperatures. To this end, bulk samples of highly doped SiC were irradiated with fast and thermal neutrons. The resultant changes in the material's electrical properties were assessed through a series of standard measurements, providing data on resistivity, free-carrier concentration and carrier mobility. These data were fit to theoretical models and analyzed for validity. Finally, following these measurements, the samples were subjected to a series of isothermal anneals at low temperature and once again their electrical properties were measured and characterized.

2. Background

2.1. Hall measurement background

We made Hall Bars with five ohmic contacts, as shown in Fig. 1 below, with the contacts denoted in the figure by bold lines that are numbered 1–5.

Resistivity is easily measured by using the definition of resistivity coupled with Ohms law, such that

$$\rho = \frac{VA}{Il} \qquad (1)$$

where V is the voltage drop along the distance of contact separation l, A the uniform cross-sectional area of the sample

* Corresponding author. Tel.: +90 436 213 0013; fax: +90 436 213 0028.
E-mail addresses: e.almaz@alparslan.edu.tr, modanoglu@gmail.com (E. Almaz).

0168-9002/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2010.06.211

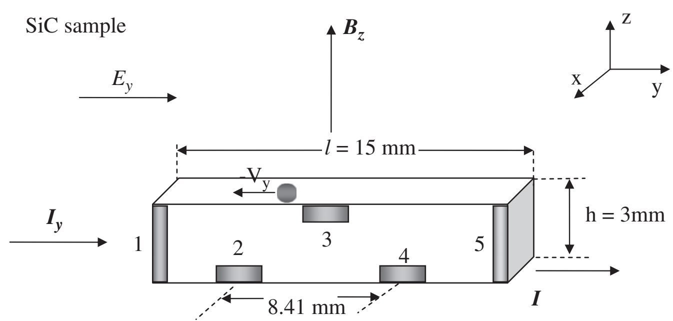

Fig. 1. Schematic of ohmic contact points and drawing of Cartesian coordinate system associated with a Hall Effect measurement.

and I the sourced current through the sample. Noting that $E=V/l$, $I=nqvA$ and $v=\mu E$, one concludes that

$$\rho=\frac{1}{nq\mu} \tag{2}$$

where v is the drift velocity, μ the mobility, n and q the density of free carriers and charge per carrier, respectively. A standard Hall Bar was constructed and utilized for the resistivity measurements to avoid introducing any errors due to non-uniform current distributions and electric fields, as can occur when Van der Pauw techniques [3,4] are used. The current was sourced in the y-direction as shown in Fig. 1.

The measurement of resistivity in the Hall bars was made in a magnetic field that was applied in the z-direction as indicated in Fig. 1. Because the current path is not complete in the x-direction, in steady state there cannot be a net flow of charge in the x-direction. An equilibrium electric field is induced in the Hall bar such that the Lorentz force on the electrons is balanced by the electrostatic force due to the induced electric field, i.e.

$$qE_x=qv_yB_z \tag{3}$$

By noting that the average carrier velocity is proportional to the current density $J_y=qv_yn$, where n is the density of free carriers, we can rewrite Eq. (3) as

$$qE_x=\frac{J_yB_z}{n} \tag{4}$$

It is customary to divide both sides on Eq. (4) by q and to set the term $1/qn$ on the right-hand side of the resulting equation equal to R_H, which is named the Hall factor. Proceeding in this customary manner, and then solving for R_H, one obtains the expression

$$R_H=E_x/J_yB_z \tag{5}$$

where $R_H=1/qn$. The numerator on the right-hand side of Eq. (5) is easily determined by measuring the voltage across the Hall bar (in the x-direction);

$$E_x=V_H/h \tag{6}$$

where h is the width of the sample. With E_x known, J_y known (the current I is sourced) and B_z known (measured), R_H can be determined. Further since q is equal to the magnitude of the charge on an electron, one can determine the carrier concentration n from R_H.

Mobility is inversely related to the resistance to motion the crystal presents to the charged carriers, which for this case are predominantly electrons. This resistance to motion is a result of scattering that occurs in the material and has many sources. Of all the scattering mechanisms that occur, phonon scattering and ionized impurity scattering are the most notable contributors. According to Mathiessen's rule,

$$\frac{1}{\mu}=\frac{1}{\mu_I}+\frac{1}{\mu_l}. \tag{7}$$

where μ_I and μ_l are, respectively, the mobilities of the sample that would exist if there were, respectively, only ionized impurity scattering or if there were only phonon scattering [5]. The electron Hall mobility in a sample can be determined from Eq. (2) rewritten as

$$\mu=\frac{1}{nq\rho} \tag{8}$$

using the measured values of the resistivity and the carrier concentration.

2.2. Irradiation effects

Neutrons are a type of non-ionizing radiation. Energetic neutrons create displacements in ordered crystals. As the radiation produces defects within the sample, the periodicity of the crystal is disturbed and deep states and trapping centers are introduced into the bulk. These states, depending on their location in the band gap, can capture free electrons from the conduction band, or more likely from donor sites present in the material. The creation of these new electron states is electrically equivalent to an acceptor concentration being introduced into the sample. As the new electron states are introduced, the number of free carriers available to conduct electricity decreases and according to Eq. (2) the sample resistivity is increased. Also, the neutron displacement damage results in the creation of new scattering centers, which act to decrease the mobility of the free electrons, and from Eq. (2) thereby further increase the resistivity in the sample.

For the case of a 1 MeV neutron interacting with a silicon atom, the average energy transferred to the primary knock-on atom (PKA) is about 66.5 keV, which greatly exceeds the kinetic energy that is required to displace a second atom from its lattice position. Consequently, collision cascades are created. Molecular dynamics simulations have been performed which show that, for a 3 keV Si PKA in SiC at room temperature, there can be upwards of 50 displacements occurring per cascade [6].

The displacement of an atom by non-ionizing radiation in SiC results in six basic types of point defects; carbon interstitials, carbon vacancies, carbon antisites, silicon interstitials, silicon vacancies and silicon antisites. Defects in the crystal can recombine to reform the perfect structure. The probability of recombination increases with increasing defect mobility. Typically the various types of defects have different mobilities and correspondingly different thermal stability. Some defects are quite mobile at low temperatures and annihilate with their counterparts. An example is a carbon interstitial hopping to a carbon vacancy, by means of thermal energy from the lattice, and recombining with the vacancy, thus erasing the effects of either. Other point defects can be quite immobile even at temperatures as high as 1100 °C.

3. Materials and methods

3.1. Overview

The data were recorded for these experiments over a four-month time period as samples were irradiated, Hall measurements were made, and the process was repeated for increasing neutron fluence. All samples were cleaned and prepared and subjected to the same irradiation conditions. All measurements were performed at the Ohio State University Nuclear Reactor Lab