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BEAM INTERACTIONS WITH MATERIALS AND ATOMS

The effect of the interfacial states by swift heavy ion induced atomic migration in 4H-SiC Schottky barrier diodes

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ABSTRACT

The effects of the atomic migration between metal and semiconductor by swift heavy ion (SHI) irradiation on the turn on voltage (V_{on}), ideality factor (n) and Schottky barrier height (SBH) in 4H-SiC Schottky barrier diodes (SBD) have been researched. The results show that the n decreases and SBH increases for 4H-SiC SBDs without irradiation and with 5×10^9 ions/cm^2 at increasing testing temperature. After irradiation, the V_{on} and SBH of the sample increases due to the forming of higher barrier height $TiSi_x$ by annealing treatment at 873 K. The SHI and annealing treatment can make the deep level defect to be partly recovered. The results may be explained that the interfacial structure was modified due to the silicon and carbon atomic migration during SHI process at the interfacial region between metal and semiconductor, and then reacting at high temperature annealing treatment.

1. Introduction

SiC Schottky barrier diodes (SBD) have several advantages that enable them to find applications in space communication systems and high temperature / power environment. In such cases, the effects of radiation on electrical contacts between metals and silicon carbide (SiC) are very important and thus have attracted a lot of attention in recent years [1–4]. However, most work has been carried out using irradiation by light particles, with few studies using irradiation by swift heavy ions (SHI). There are two main issues with SHI. The first issue concerns the physical mechanism of the formation of defects by SHI irradiation. These can be studied using Rutherford backscattering spectrometry in channeling mode (RBS/C) [5,6], scanning transmission electron microscope (STEM) [2,3], cross sectional transmission electron microscopy (XTEM) [7] and molecular dynamics simulation [2,3]. The second issue concerns the relationship between irradiation conditions and electrical properties [8,9,11], including radiation-induced metastable defects [10].

In previous work, we observed phenomena in 4H-SiC SBD due to atomic diffusion induced by SHI, using the techniques of XTEM and EDX scan. The influence on electrical performance of was not considered [11,12], and the evolution of the electrical characteristics of 4H-SiC SBD with gradually increasing operation temperature and annealing temperature has still not been studied. In the present work we study the atomic migration at the Schottky contact region arising from SHI and post-annealing treatment, and the effect on the electrical performance on 4H-SiC SBD.

2. Experimental methods

The experiments were performed using a commercial 4H-SiC SBD (reference number CSD01060) with a rated blocking voltage of 600 V, fabricated by Cree Inc. Experiments were performed using the Heavy Ion Research Facility in Lanzhou (HIRFL) at the Institute of Modern Physics, Chinese Academy of Sciences. Samples were irradiated by 9.5 MeV/u ^{209}Bi ion beam, with fluences of 5×10^9 ions/cm^2 without intentional heating. The swift heavy Bi ions passed through Al/W/WTi/Ti layers to the SiC substrate. The experiment irradiation conditions of the sample are illustrated schematically in Fig. 1. In this paper we label the pre-irradiation and irradiated samples as S0 and S1 respectively. The two sets of experiments were performed on the two samples, one as a function of temperature, and the other at room temperature after annealing 30 min in an atmosphere of purified N_2 (99.999%) at temperatures of 478 K, 678 K and 878 K.

The electrical properties of the samples were measured by Keysight B2902A (Current-Voltage, I-V). In order to calculate the parameters of

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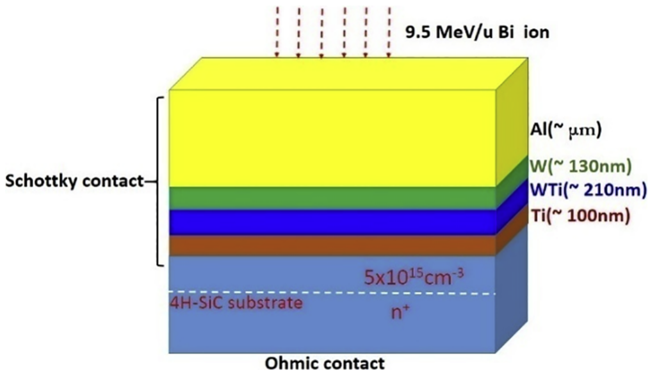

Fig. 1. The schematic of Al/W/WTi/Ti/4H-SiC Schottky barrier diode and experimental conditions of Bi ion irradiation.

the deep electron traps created by the SHI irradiation, deep level transient spectroscopy (DLTS) measurements were performing by scanning across the temperature range from 80 K to 420 K. The reverse bias voltage was set to $U_R = -6$ V and a single filling pulse voltage $U_p = 0$ V (i.e. filling pulse height was equal to 6 V). Lock-in frequencies of 180 Hz, 340 Hz,480 Hz, 640 Hz, 780 Hz and 940 Hz were used, and the width of the filling pulse was set to 50 μs. The cross-section of the samples were investigated by high resolution transmission electron microscopy (HRTEM) analysis performed on a 200 kV FEI Talos F200X instrument. The focused ion beam (FIB) (FEI Helios) technique was used to prepare the final thin cross sectional slices used in the TEM measurements.

3. Results and discussion

The forward I-V characteristics of two samples with different temperatures are shown in Fig. 2, which can be considered as stable I-V properties only at forward bias V < 0.8 V. However it is obvious that the effects of irradiation and temperature are more pronounced at high forward biases. The turn on voltage (V_{on}), which is shown in the inset in Fig. 2(a), decreases with increasing temperature. The corresponding variations of the ideality factor (n) and Schottky barrier height (SBH, ϕ_{b0}) as a function of temperature are determined using the thermionic emission theory, which are shown in Fig. 2(b). Based on the Schottky barrier thermionic emission theory [13,14], the ideality factor (n) and barrier height (ϕ_{b0}) can be obtained from the slope and y axis intercept of the fitted ln (I) ~lin (V) curve, respectively, and Eqs. (1)–(3).

$$I = I_s\left[\exp\left(\frac{q(V-IR_s)}{nkT}\right)-1\right] \quad (1)$$

$$n = \frac{q}{k_0 T}\frac{dV}{d\ln I} \quad (2)$$

$$\Phi_{b0} = \frac{k_0 T}{q}\ln\left(\frac{AA^{*}T^2}{I_s}\right) \quad (3)$$

where I_s is the saturation current derived from the straight line interception of the ln (n) axis at zero bias, n denotes the ideality factor, R_S is the series resistance, q is the elementary electron charge, k is the Boltzmann constant, T is the temperature, A denotes the diode area (0.5 mm^2), Φ_{b0} is the Schottky barrier height and A^* is the Richardson's constant, previously calculated and equal to about 146 A/cm^2 K^2 for 4H-SiC.

The decrease of n (2.53–1.29) for S0/(3.21–1.71) for S1 and the increase of SBH (0.74–1.23) eV for S0/ (0.54–1.13) eV for S1are due to increasing temperature. The dependence follow the relationship that the low $n \propto T^{-1}$[15] and SBH ~ T [16]. Meanwhile, It is also observed that the SHI leads to increase in n and decrease in SBH among 100–350 K.

Thermal treatment is widely used to obtain a stable SBH and to decrease resistance at the interface between the silicon carbide and the Schottky metal. The forward I-V characteristics of two samples with annealing treatment at temperature ranging from 473 K to 873 K are shown in Fig. 3(a). It is obvious that the effects of irradiation and annealing treatment are more notable at high forward biases. Meanwhile, the deterioration of electrical properties occurred after annealing treatment at 873 K for both samples. According to the inset Fig. 3(a), the V_{on} of two samples increases by annealing treatment at 873 K. As can be clearly see in Fig. 3(b), both n and SBH exhibit a dependence on

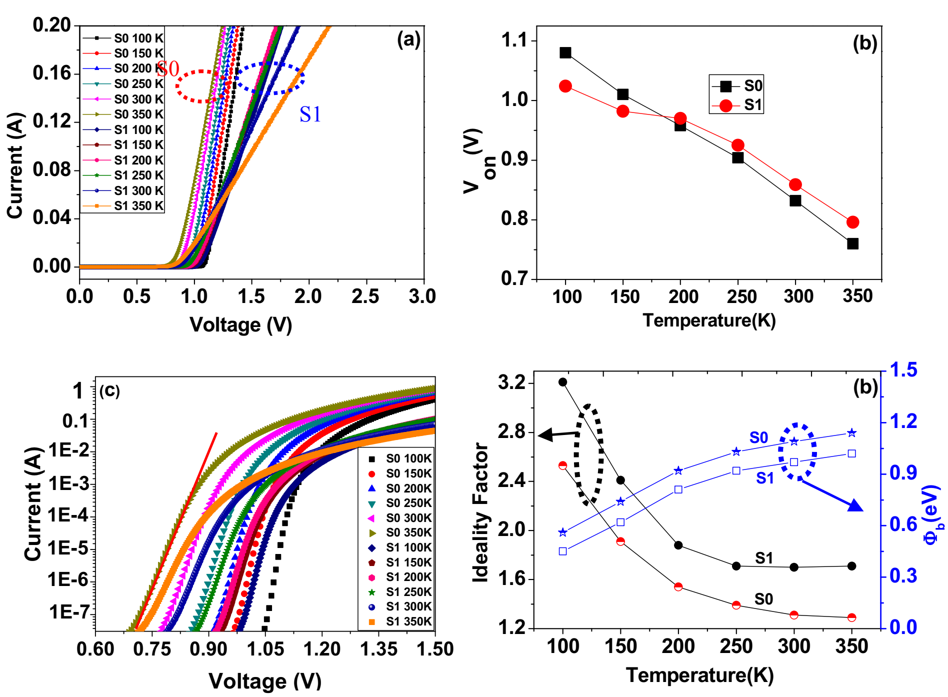

Fig. 2. (a) The forward I ~ V characteristics; (b) the dependence of V_{on} the temperature, (c) the I-V plot in semi-log scale and (b) the dependence of n and SBH on the temperature of SBDs from 100 K to 350 K.