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High resolution alpha particle detection using 4H–SiC epitaxial layers: Fabrication, characterization, and noise analysis

Sandeep K. Chaudhuri, Kelvin J. Zavalla, Krishna C. Mandal *

Department of Electrical Engineering, University of South Carolina, Columbia, SC 29208, USA

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ABSTRACT

In this article we report the fabrication and characterization of large area, room-temperature operable and very high resolution Schottky barrier detectors for alpha particles using 20 μm thick n-type 4H–SiC epitaxial layers. Schottky barriers were fabricated by depositing circular nickel contacts of ~11 mm^2 area on the 4H–SiC epitaxial layers. Room temperature current–voltage measurements revealed very high Schottky barrier height of 1.6 eV and extremely low leakage current of 3.5 pA at an operating reverse bias of −90 V. We also report an energy resolution of 0.29%, which is the best resolution obtained so far for uncollimated 5.48 MeV alpha particles in 4H–SiC epitaxial detectors with such a large area. Very low micropipe density ($< 1\ cm^{-2}$) and low effective doping concentration ($2.4 \times 10^{14}\ cm^{-3}$) in the epilayer helped to achieve a high resolution even with the large detector area and a broad source. A diffusion length of ~18.6 μm for holes has been determined in these detectors following a calculation based on a drift-diffusion model. A noise analysis in terms of equivalent noise charge revealed that the white series noise due to the detector capacitance has substantial effect on their spectroscopic performance.

1. Introduction

4H–SiC epitaxial layers have been long identified as a radiation hard and physically rugged material with superior electronic properties which are appropriate for nuclear radiation detection purpose [1–3]. Availability of high-quality bulk [4] and epitaxial 4H–SiC has revived the feasibility of fabrication of nuclear radiation detectors which are truly compact, operable at room or elevated temperature, physically rugged, and radiation hard [5–10]. In particular, SiC detectors have been demonstrated as excellent alpha particle detectors [8] and hence are being considered as compact neutron detectors when coupled with neutron–alpha conversion layers [2]. Because of large hole diffusion length [11] and achievable built-in potential greater than ~1.15 eV [6], 4H–SiC Schottky barrier detectors can also be configured for bias-less operation [12] which is a much sought-after quality for field deployment of stand-off detection for Homeland Security applications. As usually in the case of semiconductor radiation detectors, defects present in the active volume of the detector play a very crucial role in defining the overall performance of the detector. Various kinds of electrically active defects might be present in 4H–SiC epilayers [13] which can be detrimental to the required detection properties like charge carrier mobility and lifetime. Apart from defect free active volume, the pre-requisites for high-resolution and high-efficiency detection system are minimum energy scattering at the detector entrance window, efficient stopping of the ionizing particle within the effective volume of the detector (depletion region), high carrier mobility and lifetime, minimum detector leakage current and minimum noise associated with the detection front-end and filter electronics. In this article we describe the fabrication and characterization of large-area and highest resolution alpha detectors operable at room temperature. The detectors were fabricated following a very simplistic approach using 4H–SiC epitaxial detectors and taking into consideration all the above-mentioned criteria for high resolution detection. There are no reports of such high-resolution detectors present in the literature. Strokan et al. [14] reported an energy resolution of 0.34% for 5.1–5.5 MeV α-particles for detectors with area one order of magnitude less than that of the detector used in this study. Ruddy et al. [15] also reported similar energy resolution for 5499 keV alpha particles using 4H–SiC epilayer detectors with an area of ~0.79 mm^2. We have used 10 nm nickel contacts for forming Schottky junction thereby minimizing the energy dispersion at the entrance window [16]. High resistive epilayers enabled to obtain depletion width of 20 μm at reverse bias voltages as low as −90 V, which is a sufficient depth to stop most of the alpha particles from n,α nuclear reactions. Epilayers with micropipe density lower than 1 cm^{-2} helped to obtain very low leakage currents and high carrier transport coefficients. And finally, to monitor the electronic noise associated with the detector and detection electronics, we have carried out noise analysis based on an equivalent noise charge (ENC) calculation model [17].

* Corresponding author. Tel.: +1 803 777 2722; fax: +1 803 777 8045.
E-mail address: mandalk@cec.sc.edu (K.C. Mandal).

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2. Experimental methods

We have used 20 μm thick n-type epitaxial layer, grown on a 4H–SiC (0001) wafer highly doped with nitrogen and 4° off-cut towards the [11$\overline{2}$0] direction. Fig. 1 shows the cross-section of the wafer structure schematically. The effective doping concentration of the epitaxial layer was measured to be 2.4×10^{14} cm^{-3}. A micropipe defect density less than 1 cm^{-2} has been evaluated using Nomarski optical microscopy and scanning electron microscopy. Several 8×8 mm^2 SiC samples were diced from the 76 mm diameter parent wafer. The wafers were cleaned following the standard RCA cleaning procedure. Schottky barriers were formed by depositing 10 nm thick nickel contacts (circular) with an area of ~11 mm^2 on the freshly cleaned wafers using a Quorum Q150T sputtering unit. Large Ni contact (approximately 6×6 mm^2) 100 nm in thickness was deposited on the opposite surface for the back contact. The wafers were then mounted on printed circuit boards (PCB) and wire-bonded. The wire-bonding was done using very thin (25 μm) gold wire to ensure less scattering and obscuration of the alpha particles from the wire-bond region. The PCBs were fitted with board-to-board connector pins in order to obtain plug-in modular configuration for stable electrical connections.

The Schottky barrier electrical properties were studied at room-temperature using current–voltage (*I–V*) and capacitance–voltage (*C–V*) measurements. Pulse-height spectra of alpha particles were recorded using an analog spectrometer comprised of an Amptek A250CF preamplifier, an Ortec 572 spectroscopy amplifier, and a Canberra Multiport II ADC-MCA unit. The detectors under test were placed inside a metal box which was being constantly evacuated (~10^{-3} mbar) during the measurements. A negative bias was applied to the Schottky contact for reverse biasing the detector. A 0.1 μCi ^{241}Am alpha source with an active diameter of 7 mm was placed inside the box and above the detector (facing the Schottky contact) at a vertical distance of 12 mm which ensures a full illumination. The energy calibration of the detection system was carried out using a precision pulser. The energy resolution was expressed in terms of full width at half maxima (FWHM) and percentage resolution of the relevant peaks. For the electronic noise measurements, a precision pulser was fed to the pre-amplifier input using a calibrated feed-through capacitor and pulse height spectra were obtained. The width of the pulser peak expressed in terms of Coulomb rms was used as the equivalent noise charge. For measuring the ENC with the detector connected, the pulser was fed through the pre-amplifier test input.

3. Observations and discussions

3.1. Electrical characterization

Fig. 2 shows the variation of forward and reverse currents as a function of applied bias. The detector leakage current at a reverse bias voltage of −110 V was observed to be ~4.32 pA. However the detectors were operated at lower bias voltages, as the full-depletion was achieved at around −90 V reverse bias. From the forward *I–V* characteristics, the barrier height and the diode ideality factor were calculated to be 1.6 eV and 1.2 respectively using a thermionic emission model [18] given by

$$I = A^*AT^2(e^{-\beta\varphi_B})\left(e^{\frac{\beta V}{n}}-1\right) \quad (1)$$

where A^* is the effective Richardson constant (146 A cm^{-2} K^{-2} for 4H–SiC), A is the area of the diode, φ_B is the Schottky barrier height, n is the diode ideality factor, V is the applied voltage, and $\beta=q/k_BT$, q being the electronic charge, k_B the Boltzmann constant, and T the absolute temperature. The obtained barrier height of 1.6 eV is high enough to offer very good rectification properties.

Fig. 3 shows the $1/C^2$ vs. V plot obtained for one of the detectors. The plot was fitted with a linear function to obtain an effective doping concentration (N_{eff}) of 2.4×10^{14} cm^{-3}. The original *C–V* plot shown in the inset shows that the detector junction capacitance at an operating reverse bias of −90 V is 55.2 pF. It can also be noticed from Fig. 3 that the capacitance value saturated beyond a reverse bias of −90 V. The depletion width (d) at −90 V was calculated to be ~20 μm, using Eq. (2), which is equal to the thickness of the epilayer itself and hence the junction capacitance value did not change beyond −90 V.

$$d=\sqrt{\frac{2\varepsilon\varepsilon_0 V}{qN_{eff}}} \quad (2)$$

where ε is the dielectric constant of 4H–SiC (9.7), ε_0 is permittivity of vacuum, V is the applied bias and q is the electronic charge.

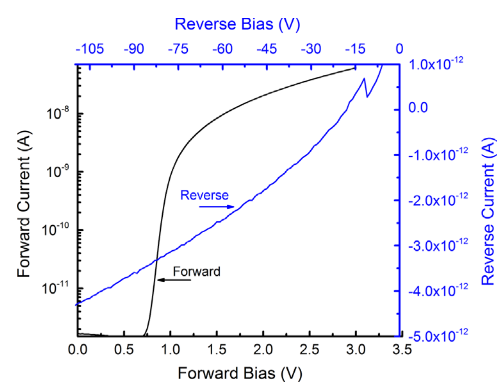

Fig. 2. Room temperature *I–V* characteristics at forward and reverse bias for an n-type 4H–SiC epitaxial Schottky detector.

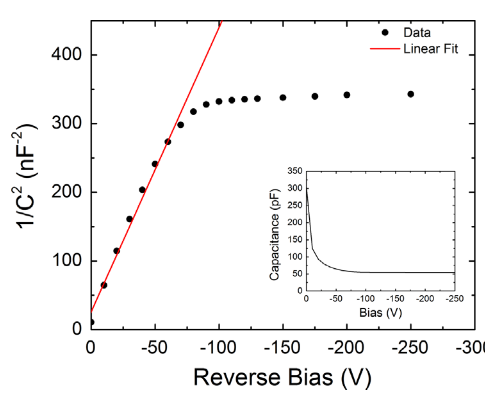

Fig. 3. $1/C^2$ vs. V plot for an n-type 4H–SiC Schottky barrier detector (Inset shows the original *C–V* plot).

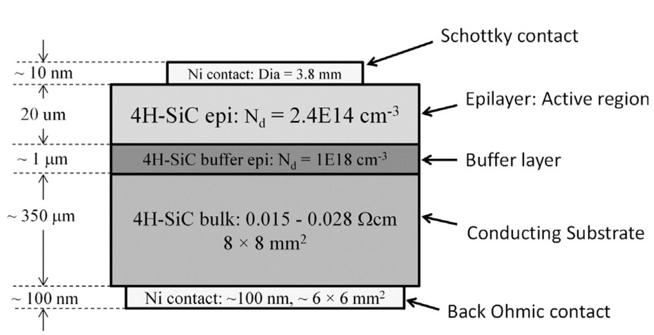

Fig. 1. Schematics of the 4H–SiC wafer used for fabrication of Schottky barrier detectors.