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High-temperature performance of gallium-nitride-based *pin* alpha-particle detectors grown on sapphire substrates

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ABSTRACT

The temperature-dependent radiation-detection performance of an alpha-particle detector that was based on a gallium-nitride (GaN)-based *pin* structure was studied from 290 K to 450 K. Current–voltage–temperature measurements (*I–V–T*) of the reverse bias show the exponential dependence of leakage currents on the voltage and temperature. The current transport mechanism of the GaN-based pin diode from the reverse bias *I–V* fitting was analyzed. The temperature-dependent pulse-height spectra of the detectors were studied using an ^{241} Am alpha-particle source at a reverse bias of 10 V, and the peak positions shifted from 534 keV at 290 K to 490 keV at 450 K. The variation of full width at half maximum (*FWHM*) from 282 keV at 290 K to 292 keV at 450 K is almost negligible. The GaN-based *pin* detectors are highly promising for high-temperature environments up to 450 K.

1. Introduction

Gallium nitride (GaN) possesses numerous attractive characteristics, such as a wide band-gap (3.43 eV), a large displacement energy and a high thermal stability, which make it suitable for ionizing-radiation detection [1–10]. GaN-based alpha-particle detectors and neutron detectors have been fabricated using various device structures on substrates such as free-standing GaN, sapphire and silicon carbide (SiC) [11–14]. The maximum charge-collection efficiency (*CCE*) of GaN-based alpha-particle detectors is close to 100%, whereas the *FWHM* of the energy resolution is less than 30% because the space charge region (*SCR*) width from the available thickness of the epitaxial GaN is limited by the background carrier concentration [11,15]. Recently, several groups have investigated the effect of high-energy radiation on the performance of GaN-based detectors. For example, Grant et al. [16] investigated the *CCE* of post-irradiation GaN-based Schottky barrier detectors grown on sapphire substrates, using various fluences with 24 GeV/c protons and 1 MeV neutrons, respectively. They found that the maximum *CCE* of the investigated detectors was 26%, which is lower than that of an unirradiated device (53%). Mulligan et al. [17] reported the spectrometry performance of GaN-based Schottky detectors grown on a free-standing 450-μm-thick GaN substrate. Their results suggest that the detection performance of their detectors is stable after in-core neutron irradiation of 10^{15} cm^{-2}. Most recently, the temperature-dependent performance of GaN-based detectors has attracted great interest because the clean signal exceeds the noise. For instance, Owen et al. [13] investigated the pulse height spectra of GaN-based *pin* detectors grown on p-type 4H-SiC substrates, using 5.5 MeV alpha-source irradiation at −10 V bias at 233 and 293 K, respectively. The spectral *FWHM* (energy resolution) deteriorated from 20% (233 K) to 25% (293 K). The peak center position and *F WHM* changed linearly with increasing temperature. Polyakov et al. [14] investigated the properties of GaN alpha-particle detectors using an epitaxial lateral overgrowth technique over different GaN epilayers from 23 to 333 K and found that the *CCE* was nearly 100%, even above 333 K. However, thus far, few reports exist on experimental support for the high-temperature performance of a GaN radiation detector, and more systematic studies are required. We investigated the temperature-dependent radiation-detection performance of an alpha-particle detector based on a GaN *pin* structure on sapphire substrates from 290 to 450 K. We studied the electrical properties of the detector by *I–V* measurements and the detector was irradiated by

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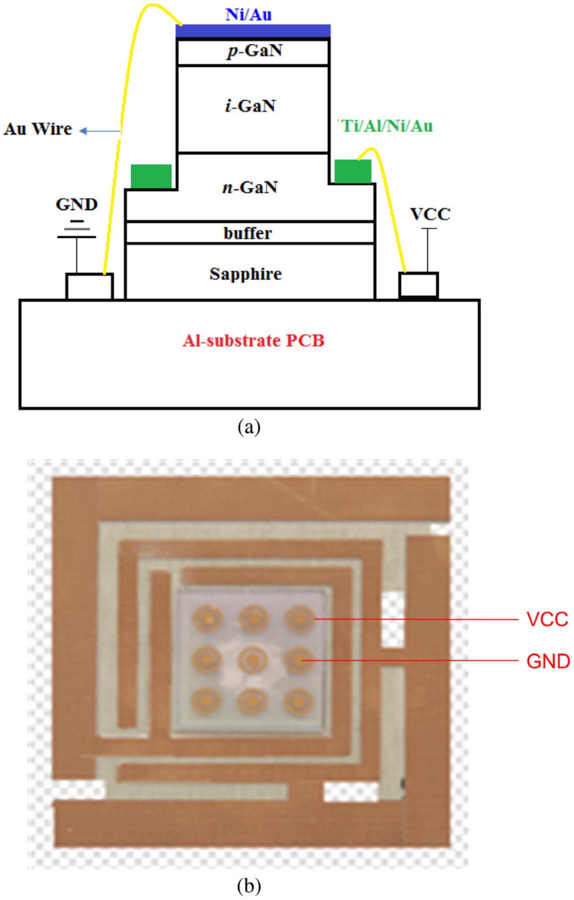
^{241}Am. Such results are of critical importance to improve GaN-based radiation-detector performance.

2. Experimental details

GaN-based *pin* detectors were grown on (0001) sapphire substrates by metal–organic chemical vapor deposition (MOCVD). The p -GaN/i -GaN/n -GaN epilayer structures included a 2-μm-thick Si-doped n -GaN layer, a 5-μm-thick undoped (i) GaN layer, and a 300-nm Mg-doped p -type GaN layer to form the *pin* diode structure, as is shown schematically in Fig. 1a. After depositing Ti/Al/Ni/Au (20/50/20/300 nm) on the n-GaN layer, the sample was annealed at 823 K for 900 s in nitrogen, which resulted in the formation of n-GaN Ohmic contacts. Ni/Au (20/300 nm) was deposited on the p-GaN layer and annealed at 773 K in air for 900 s. The preparation of Ohmic contacts was patterned by electron beam equipment and by the lift-off of a lithographically defined photoresist. Mesa structures of GaN-based *pin* detectors of 1-mm diameter were etched from the p-GaN down to the n-GaN layer by inductively coupled plasma dry-etching processing without surface-passivation treatment. The *pin* detectors were mounted on the Al-substrate printed circuit board (*PCB*) with gold-plated contacts and were wire-bonded using a gold wire with a 25-μm diameter to ensure the reliability of the device measurement temperature, as shown in Fig. 1b. GaN-based *pin* detectors and the ^{241}Am source with the energy of 5.48 MeV were housed in a Lake Shore Model TTPX cryogenic-probe station with a base pressure less than 1 Pa to minimize the particle-energy loss. Liquid nitrogen was used as a refrigerant for temperature stability, and Lake Shore 336 was applied to control the sample temperature with an accuracy of 0.1 K. A Keithley 4200 was used to measure the *I–V* electrical properties of the devices from 290 K to 450 K. The ^{241}Am alpha-particle pulse-height spectrum was measured using a standard pulse-height analysis Ortec setup, and was composed of a charge-sensitive preamplifier 142PC, a shaper amplifier 572 A with a shaping time of 1 μs and a multi-channel pulse-height analyzer 927. The spectrum of counts versus channel number was viewed on the computer using the Maestro software program. Because of the effect of temperature on the ^{241}Am radioactive source, the distance from the ^{241}Am radioactive source to the detector was 50 mm for safety.

3. Results and discussion

Fig. 2 shows the reverse *I–V* characteristic curves of the *pin* detectors at 290, 330, 370, 410, and 450 K. All *I–V* curves showed that the leakage current increased exponentially with the reverse bias. The leakage current of devices that were obtained from the *I–V* curves for a reverse bias of 10 V were 1.2, 5.0, 5.6, 8.2 and 13.9 nA at 290, 330, 370, 410, and 450 K, respectively. The leakage currents also increased exponentially with temperature for a given reverse bias in Fig. 3. According to the above experimental results, the exponential dependence of leakage currents on the voltage and temperature cannot be explained by the Sah–Noyce–Shockley model for a diffusion component and the generation–recombination current in the reverse bias $p-n$ junction [18]. Fig. 2 shows that the *I–V* curves of the reverse bias have two segments, of 1 to 7 V and more than 10 V, respectively, which correspond to solid and dashed lines and show that the device's reverse-leakage-current transport mechanism is different for different voltage ranges. According to Ref. [19], for a reverse bias of 1 to 7 V (moderate electric field), carrier-hopping conduction through defect-related states under the action of an electric field may be the dominant current transport mechanism. For a reverse bias above 10 V (high electric field), the Pool–Frenkel emission of carriers from a trap may be the other current transport mechanism [20]. The leakage current characteristics are likely to be associated with thermally generated carriers and enhanced carrier hopping through dislocations or traps [21], which results in a heat-activation energy in the deep-jump center, and electrons in the depletion region pass through the conduction band that make the current increase exponentially [22].



(a)

(b)

Fig. 1. (a) *Pin* device structure; (b) photograph of nine detectors bonded bound to Al-*PCB* with gold-plated contact. External ring electrode (Ti/Al/Ni/Au) and internal circular electrode (Ni/Au) were connected to probes on a TTPX cryogenic probe station arm with applied voltage VCC and GND, respectively.

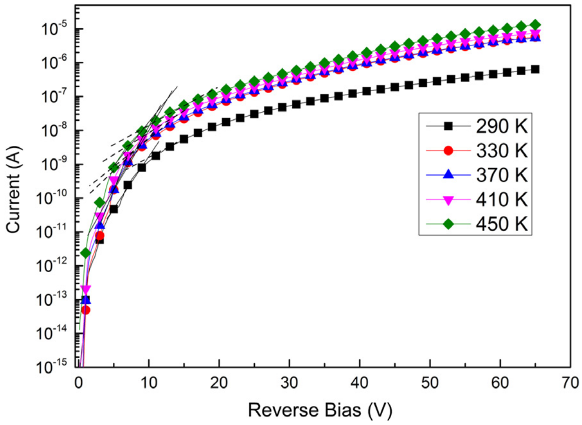


Fig. 2. *I–V* characteristics of GaN-based *pin* detectors from 290 K to 450 K under various reverse bias.

For our *pin* devices, as shown in Fig. 2, the leakage currents of devices for a reverse bias of 10 V were found to be less than 1.2 nA at 290 K and increased to only 13.9 nA at 450 K, which indicates the attractive high-temperature reliability of the GaN-based *pin* detector.

Prior to measuring the alpha-particle spectrum of a GaN *pin* detector, an Ortec's Si *pin* detector and a 5.48 MeV ^{241}Am source were used for energy calibration. No collimator was used for the alpha source.