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Alpha-particle detectors with GaN PiN homoepitaxial layer

Hironori Okumura[1], Yohei Ogawara[1], Manabu Togawa[2], Masaya Miyahara[2], Jiro Nishinaga[3], Masataka Imura[4], and Tadaaki Isobe[5]

[1] The Univ. of Tsukuba
Tennoudai 1-1-1, Tsukuba, Ibaraki, 305-8577, Japan
E-mail: okumura.hironori.gm@u.tsukuba.ac.jp
[2] KEK
Oho 1-1, Tsukuba, Ibaraki, 305-0801, Japan
[3] AIST
Umezono 1-1-1, Tsukuba, Ibaraki, 305-8568, Japan
[4] NIMS
Namiki 1-1, Tsukuba, Ibaraki, 305-0044, Japan
[5] RIKEN
Hirosawa 2-1, Wako, Saitama, 351-0198, Japan

Abstract

We report on the first demonstration of an alpha-particle detector using vertical GaN-on-GaN PiN structure. A differential on resistance for 100 A/cm^2 and breakdown voltage of a GaN PiN diode were 5 mΩcm^2 and 444 V, respectively. The ideality factor and leakage current for a 100 μm diode were 2 and <10^{-8} A/cm^2, respectively. A signal pulse from an alpha article was detected at room temperature in air using the GaN PiN diode.

1. Introduction

Semiconductor radiation detectors have advantages of compact size, fast timing characteristics, and superior energy resolution. Ionization radiation generates electron-hole (e-h) pairs by passing through a depletion region in a semiconductor diode. The electrons and holes are diffused to electrodes by an applied electric field, resulting in a signal pulse recorded by an external circuit. Si and Ge detectors are primarily used for charged particle spectroscopy.[1] However, Si and Ge detectors are operated at low temperature to reduce thermally generated leakage current. Wide-bandgap semiconductors are attractive for room-temperature operation and radiation tolerance. Especially, GaN has a high carrier mobility, which enhances charge collection, a high effective atomic number, which increases photoelectric absorption, and large displacement energy, which contributes to a good detector lifetime.[2] Still, there are no reports on radiation detectors using GaN-on-GaN PiN diodes.

In this study, we fabricated vertical GaN PiN diodes as alpha-particle detectors.

2. Experimental procedures

We used the GaN homoepitaxial layer grown on a 2-inch n-type GaN substrate, which has a threading dislocation density of ~10^6 cm^{-2} and [Si]=2×10^{18} cm^{-3}, by MOCVD (SCIOCS). As schematically shown in Fig. 1, the PiN structure consisted of 500-nm p-GaN ([Mg]=1×10^{18} cm^{-3})/ 10-μm n$^-$-GaN ([Si]=1×10^{16} cm^{-3})/ 2-μm n-GaN ([Si]=1×10^{18} cm^{-3}) layers with a 50-nm p$^+$-GaN ([Mg]=2×10^{20} cm^{-3}) contact layer.

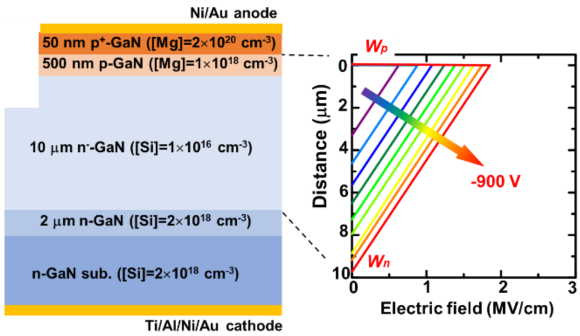

Fig.1: Schematic cross-section of vertical GaN PiN detectors and the relation of depletion width and electric field in GaN PiN structure at reverse biases between -100 and -900 V.

With assuming mean excitation energy of 8.9 eV for GaN, the number of e-h pairs generated in passing an alpha particle is estimated to be 3.4-6.2×10^4 μm^{-1} using GEANT4. An incident alpha particle loses the energy at a depth of ~12 μm. This means that an alpha particle stops in the GaN epilayer. The number of generated e-h pairs increases with increasing a depletion width. At a reverse bias of 953 V, the n$^-$-GaN layer is fully depleted and the p-GaN layer has the depletion width of 50 nm, generating the maximum electric field of 1.95 MV/cm, which is smaller than the critical electric field of GaN. Thus, the maximum number of e-h pairs, or signals, is estimated to be ~5×10^5.

After cutting the sample to the size of 5 mm × 4 mm, we fabricated GaN PiN diodes with anode diameters between 100 and 1000 μm. Ti (20 nm)/Al (100 nm)/Ni (10 nm)/Au (50 nm) electrodes were evaporated on the sample backside using EB deposition, followed by thermal annealing at 800°C for 1 min in a nitrogen ambient. The 900-nm-thick mesa structure was fabricated using RIE with a Cl_2/BCl_3 (50 sccm/ 20 sccm) mixture gas at ICP power of 150 W at pressure of 5 Pa. After Ni (25 nm)/Au (25 nm) electrodes were deposited, thermal annealing was carried out at 500°C for 10 min in an oxygen ambient. Current-voltage (*I*-*V*) and capacitance-voltage (*C*-*V*) characteristics were measured using a parameter analyzer.

The sample was mounted on a package (KD-S770047-G) with silver paste. Anode electrodes were bonded to each pin with a 40-μm thick Al wire. An amplifier-shaper-discriminator integrated circuit with 8 channels was used to read a detection signal. The detector capacitance including coaxial cable was 22 pF, causing equivalent noise charge of 2×10^3. This means that the maximum signal-to-noise ratio is 300, which is enough high to detect the signal from an alpha particle. We used the alpha particles from an Americium-241 radioactive source with the energy of 5.48 MeV, which was perpendicularly put on the package within 1 cm in air. The signal pulse was measured at room temperature in air by an oscilloscope.

3. Results and discussion

An *I-V* characteristic of the GaN PiN diode with a diameter of 100 μm is shown in Fig. 2. The GaN PiN diode exhibited a good rectifying behavior with a forward current of 100 A/cm^2 at 3.7 V. A differential on-resistance was 5 mΩcm^2 for 100 A/cm^2. The sheet resistance and contact resistivity of the p-GaN layer were 8.4×10^4 Ω/□ and 1.3×10^{-2} Ωcm^2, respectively. The differential on-resistance could be further reduced by decreasing the p-contact resistivity. The on/off current ratio was ~10^9. The apparent turn-on voltage was 3.2 V. The breakdown voltage without flourinert was 444 V, which is much smaller than the reverse voltage required for full depletion of the n$^-$-GaN layer. The surface passivation and field-plate structure would increase the breakdown voltage.

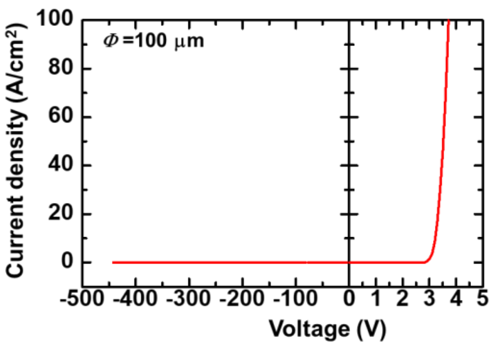

Fig. 2: Current-voltage characteristics of GaN PiN diode with a diameter of 100 μm.

The dependence of anode diameters on *I-V* characteristics at the biases between -10 V and 5 V is shown in Fig 3 (a). Leakage currents were less than 10^{-8} A/cm^2 for 100 and 200 μm diodes, while leakage currents dramatically increased for 400 and 1000 μm diodes. The ideality factor for 100 and 200 μm diodes was almost 2 in the voltage range of 2.4-3.2 V due to the Shockley-Read-Hall recombination current, while the ideality factor increased with increasing the anode diameter. We suggest that the large ideality factors for 400 and 1000 μm diodes are attributed to threading dislocations in GaN.

A *C-V* characteristic of the GaN PiN diode with a diameter of 100 μm is shown in Fig. 3 (b). $1/C^2$-V has the linear relation. The net doping concentration is estimated to be 2.7×10^{16} cm^{-3}, close to [Si] in the n-GaN layer. The built-in voltage (V_{bi}) is extracted to 5.0 V. The capacitance at 0 V was 1.2 PF due to V_{bi}. The depletion region increases as the reverse bias increases, resulting in lower capacitance. In our detectors, the detector capacitance is dominant for the equivalent noise charge.

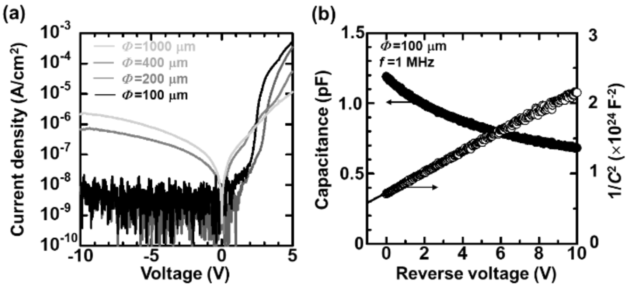

Fig. 3: (a) Current-voltage characteristics of GaN PiN diodes with diameters between 100 and 1000 μm. and (b) Capacitance-voltage characteristics of GaN PiN rectifier with a diameter of 100 μm at 1 MHz at room temperature.

The signal from an alpha particle using the GaN PiN diode without mesa structure at the reverse bias of 6 V is shown in Fig. 4. The output voltage and a FWHM value of the first pulse were 0.15 V and 100 ns, respectively. This indicates that an alpha particle was detected by the GaN PiN diode. The input e-h pairs are calculated to be 1.5×10^5 from the analog gain of 6.3 V/ pC, corresponding to depletion width of 2.4-4.4 μm, which is around three times larger than the expected depletion width of 1.1 μm at the reverse bias of 6 V. We suggest that the discrepancy of depletion width is attributed to a high incident angle of the alpha particle.

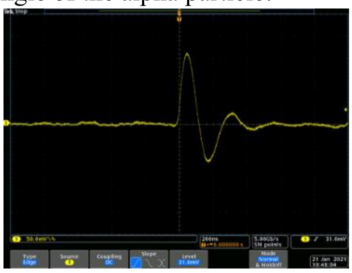

Fig. 4: Oscilloscope trace of signal from ^{241}Am using GaN PiN diode with a diameter of 100 μm.

3. Conclusions

We fabricated vertical GaN PiN diodes. A differential on resistance for 100 A/cm^2 and breakdown voltage of a GaN PiN diode were 5 mΩcm^2 and 444 V, respectively. A signal from an alpha article was detected using the GaN PiN diode. GaN PiN diodes have great potential for radiation detectors.

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