Development of GaN radiation detectors for use in the current mode

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Abstract: A current mode GaN detector is developed by using large area semi-insulting GaN crystal as its sensitive medium. The characteristics of the detector are tested such as the I-V curve, the responsibility and sensitivity to γ-rays, the charge collection efficiency, and the time response to pulsed X-rays. The test results show that a low resistance ohmic contact is formed between the crystal and the metal electrode. The dark current is lower than 400pA at voltage of 600V, the charge collection efficiency is greater than 40%, and the time response to pulsed X-rays is at nanosecond order.

Keyword: GaN; radiation detector; charge collection efficiency; sensitivity

1 Introduction

Gallium nitride (GaN) is the third generation of semiconductor material, it has a large band gap, high thermal conductivity, low dielectric constant, high drift speed, *etc.* [1]. So it has been widely applied in high power microwave device and light-emitting diode [2][3]. Radiation detectors based on GaN material have small volume, high radiation resistance, low noise, and fast response, can be used to replace the traditional Si radiation detector applied in the field of nuclear plant radiation detection and space radiation detection [4]. Energy spectrum counting detection technology based on GaN material has been developed since the 1980s, GaN film detectors with schottky contact only 10 μm has been repaired and radiation experiments to X-ray have been conducted [5]. Limited by the technique of high-quality GaN single crystal material growth, development of GaN radiation detector and GaN pulsed radiation detection technology has never been explored yet. This seriously impedes the development and application of GaN pulsed radiation detection technology. In this paper, based on SI-GaN crystal material with low defect density, we develop current mode large area radiation detector for pulsed radiation measurement.

2 Preparation of current mode GaN detector

The preparation process of the detector is a series of steps to optimize the preparation process, mainly includes four parts: wafer material selection, surface mechanical and chemical treatment, the electrode preparation and detector package. SI-GaN wafer we use is provided by the Suzhou Institute of Nanotechnology and bionics, we adopt the following technical solutions: using no defect, uniformly oriented nano-pillar array as a starting material, regulating growth parameters about growth temperature, pressure, and V/III ratio, to grow and complicate GaN material gradually at the top of nano crystalline pillar so as to form a continuous single crystal substrate material. The design of unique structure reactor body uses GaN material's negative temperature coefficient solution characteristic in liquid ammonia. Combining the advantages of hydrogen gas phase epitaxy (HVPE) and ammonothermal method, we realize the preparation of large area, high quality GaN single crystal materials. HVPE method are used to get the GaN seed crystal. And on this basis, using the method of ammonothermal, regarding it as a seed crystal again, using HVPE methods, eventually form the chip with geometry size of Φ 10 mm × 0.2 mm, resistivity larger than 10^{11}Ωcm, defect density less than 10^6cm^{-2}. Current mode GaN detector adopts different surface of metal-semiconductor and metal structure, its structure is shown in Fig. 1. The current detector we develop uses high resistivity semi-insulating GaN material with non-rectifying characteristics of ohmic contact metal electrode coated on both sides of the crystal,

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which does not require a PN junction to get a lower dark current. Ohmic contacts do not produce significant additional impedance, and do not change the equilibrium carrier concentration within the semiconductor significantly. Multilayer coated metal electrode probe method is adopted in this ohmic contact electrode production process [6], in turn, use the four layers of Ti, Al, Ni, Au electrode preparation technology, and electrode thicknesses of each layer are 220Å 1400Å 550Å 450Å respectively. Figure 2 shows a typical relationship between GaN crystal and the PCB board, on a typical PCB board, there are positive electrodes and positive area, which are internal connected, and negative electrodes and negative area which are also internal connected. But the positive and negative areas are not connected. GaN crystal with four layers of electrodes are fixed onto the PCB board using silver. Then we respectively connect the electrodes which are coated onto both sides of GaN crystal to positive and negative areas of PCB board using Au wires. Then the voltage is added between the positive and negative electrodes on PCB board, and then the voltage is also added between two sides of electrodes coated onto both sides of GaN crystal. In order to avoid electromagnetic noise, we package the detector using Al metal capsule with polythene supporter, the current mode GaN detector is shown in Fig. 3.

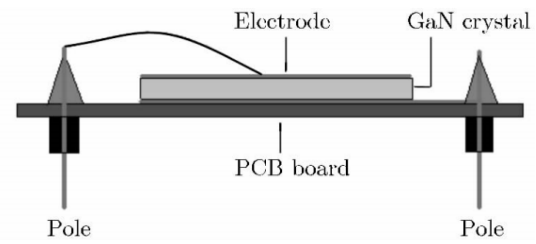

Fig.1 Schematic diagram of the GaN detector.

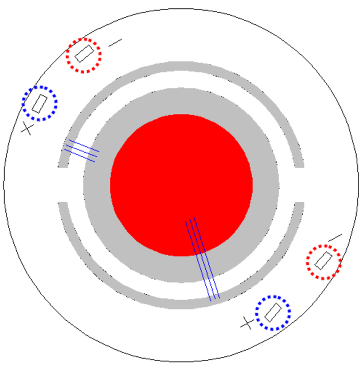

Fig.2 Relationship between GaN and PCB board.

Fig.3 Current mode GaN detector.

3 Performance of current mode GaN detector

3.1 Volt-ampere (I-V) characteristic

Dark current (I) is a critical parameter for a current mode GaN detector performance, lower dark current usually leads to a higher signal-to-noise ratio in radiation field measurement. GaN wafer quality directly influences the dark current, generally, the dark current will increase linearly as the applied voltage increases in current semiconductor detectors with good ohmic contact. The volt-ampere characteristics of the detector, *i.e.*, I-V curve can help identify electrode contact quality as well as detector material resistivity and other important information. The current mode GaN detectors we develop are photoconductive detector, so we choose dark environment during the I-V measurement, measurement system layout is shown in Fig. 4. We use regulated voltage DC power supply of STANFORD RESARCH SYSTEMS INC PS350 model to supply voltage to GaN detector, and galvanometer of KEITHLEY 6517B model to measure the current signal of GaN detector, while the detector working voltage varies between -600V and +600V, the I-V curve is shown in Fig. 5. Experimental result shows that in the working voltage range, the dark current of the detector and the applied voltage have a good linear relationship, GaN crystal surface and Ti, Al, Ni, Au metal electrodes form a good ohmic contact; Calculation results of I-V curve show that the resistivity of GaN crystal we develop is higher than $10^{14}\Omega\cdot$cm, and when the detector working bias voltage increase to 600V , the detector dark current remains below 400pA, it indicates that the detector we develop is an excellent low-noise detector.

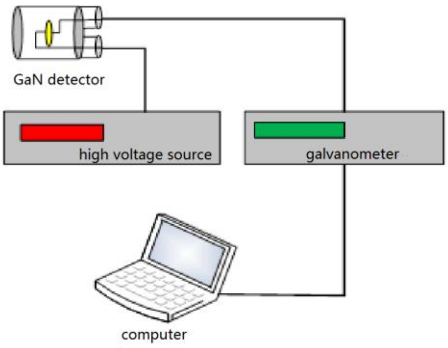

Fig.4 I-V measurement layout.

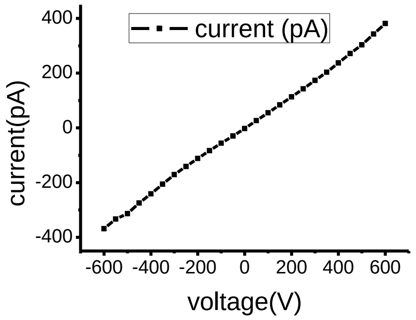

Fig.5 Dark current characteristic of GaN detector.

3.2 Response characteristics to ^{60}Co γ

In order to test the performance of current mode GaN detector, 10 thousand Curie-grade cobalt source ^{60}Co γ-ray (average energy of 1.25MeV) instrument in the Northwest Institute of Nuclear Technology has been adopted for our developed GaN detector radiation response testing. Radiation source is set in a lead shielded irradiator, where radiation source is controlled by a shutter. Firstly, we determine the parameter of radiation field, we use 0.6cc standard air ionization chamber and UNIDOS dosage meter to measure the exposure rate of position which is 1 meter far away from the radiation source center, then we calculate that the fluence rate of the radiation field is 3.65×10^{9} photon cm^{-2} s^{-1}. In order to ensure the measurement certainty, we adopt substitution method, that is, we place the GaN detector at the same position of the air ionization chamber, the experimental system arrangement is shown in Fig. 6, where the current measuring device is same as that mentioned in section 3.1, there is aluminum foil incident window in the fore end of the GaN detector. Then we study the time response characteristics in a particular bias, the measuring steps are as follows: Apply bias voltage of 200V, when the amplitude fluctuation of dark current signal stabilizes within 2%, open the shutter of ^{60}Co γ-ray source, record current signal fluctuation of the detector. Until the fluctuation of detector current signal variation exceeds the range of 2%, close the shutter of ^{60}Co γ-ray source, record current signal of the detector, and when the current signal decreases back to the dark current level. The relationship of detector current signal and time in the test is shown in Fig. 7. In our experiment, the shutter of radioactive device is opened at the 70 second, detector signal does not reach stable value immediately, but gradually stabilizes after about 200s. The qualitative analysis of this phenomenon is: in order to achieve high resistivity, during the growth of the GaN material [7], Fe doping method is used, so Fe doped and other impurities during the growth process of GaN become to be the deep level defects in GaN material, and the deep level defects form trapping center of trapping carriers. When the detector has not been irradiated, the intrinsic carriers exist in detector is balanced between effects of capture and release; When irradiation is carried out on the detector, a large number of non-equilibrium carriers generated in the GaN material, part of the carriers are captured by trapping center, because of trapping centers reduce, on-equilibrium carriers also reduce the probability of capture, so the current signal increases and reaches a stable value after a period of time. Then, we study the relationship between the stable current signal and the bias, the results are shown in Fig. 8, the curve shows that the current mode GaN detector we develop has a good linear relationship between the steady current signal and bias. Furthermore, we get the response signal to 10000 Curie ^{60}Co gamma source through comparative calculation with previous measurement of dark current calculation, and the signal-to-noise ratio is as high as 200:1. The results show that this current mode GaN has good linear response, very suitable for ray radiation measurement of high fluency rate.

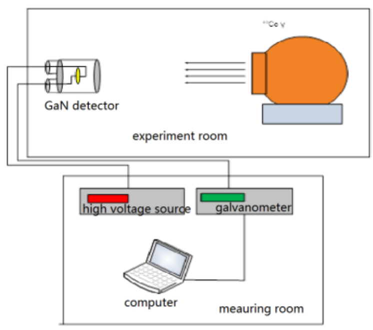

Fig.6 Measurement system layout under γ radiation.

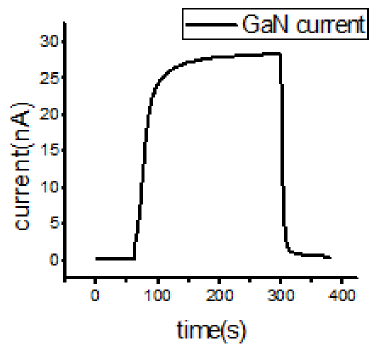

Fig.7 Time characteristic of the signal under γ irradiation.

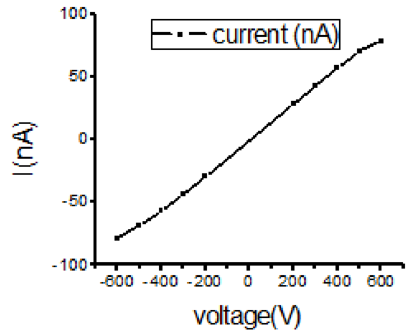

Fig.8 γ response under different bias.

3.3 Detector sensitivity for ^{60}Co γ ray

Detector sensitivity represents the level of output current I (unit A) and the intensity of radiation Φ(E) (fluence rate ,unit $cm^{-2}\cdot s^{-1}$) , that is, in per unit square, the expectation value of the detector output signal, when a particle with certain energy of E is projected into the sensitive volume, the relation is as follows:

$$S_{particle} = I / \Phi(E) \qquad (1)$$

Irradiation dose rate radiation field UNIDOS dosimeter is used in measurement, and then using air quality we can obtaine γ-ray absorption the coefficient fluence rate, finally, we calculate detector sensitivity to ^{60}Co γ-ray, the results are shown in Table 1.

Table 1 Detector sensitivity to 1.25MeV γ-ray

Detector bias (V)	Current signal (nA)	Radiation flux (γ/(cm^2 s^1))	Sensitivity (C cm^2/γ)
-600	-78.8	3.65E+09	2.16E-17
-500	-68.4	3.65E+09	1.87E-17
-400	-56.9	3.65E+09	1.56E-17
-300	-43.6	3.65E+09	1.19E-17
-200	-29.4	3.65E+09	8.05E-18
200	28.3	3.65E+09	7.75E-18
300	42.9	3.65E+09	1.18E-17
400	56.6	3.65E+09	1.55E-17
500	70.2	3.65E+09	1.92E-17
600	78.1	3.65E+09	2.14E-17

3.4 Detector charge collection efficiency

For semiconductor detectors, the formation of the detector signal is divided into two process: production and transportation of carrier. Due to the impurities or defects that exist in the semiconductor material, the carrier traps form on their transmission line, carriers are captured with a certain probability when they meet these traps, so carriers can't be completely collected. Thus, using the ratio of the amount of charge collected in the external circuit detector to the total charge amount of carriers produced by radiation to represent the detector charge collection efficiency (CCE) η. In this paper, γ-ray energy deposition in the detector is calculated by particle physics simulation software which is based on Monte Carlo method, we assume that all the energy deposited in crystal is used to produce electron-hole pairs, the average ionizing energy of GaN we use is 8.9eV which is obtained from the semiconductor material literature, and we get the theoretical sensitivity result which is 5.25×10^{-17} C cm^2/γ. By this method the charge collection efficiency of the detector can be considered as the ratio of experimental sensitivity to theoretical sensitivity, Fig. 9 shows the relationship between charge collection efficiency and the bias. From the result we can see that the detector charge collection efficiency increases approximately linearly with the bias, especially at the voltage of 600V, the charge collection efficiency can reach 40%.

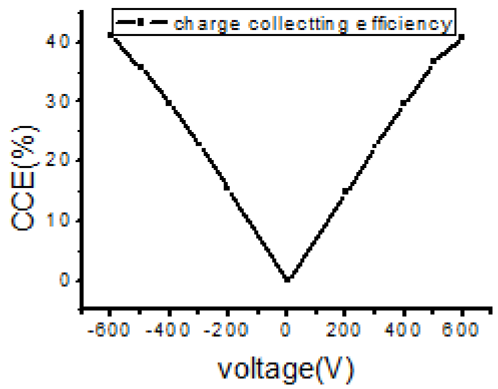

Fig. 9 Relationship between charge collection efficiency and bias.

3.5 GaN detector pulse response

Pulse response time is an important parameter for current mode semiconductor radiation detectors, and is also the foundation for measuring intense pulse radiation environments. Current mode GaN detector pulse response time is measured with repetition frequency of sub-nanosecond hard X-ray source techniques developed by the Northwest Institute of Nuclear Technology, measurement layout and results are shown in Figs. 10 and 11. Measurement results show that when the pulse half width of the X-ray is 800ps, FWHM of the GaN detector response signal is only 1ns. Therefore, this current mode GaN detector has a sub-nanosecond magnitude response characteristics for diagnosis of nanosecond radiation field.

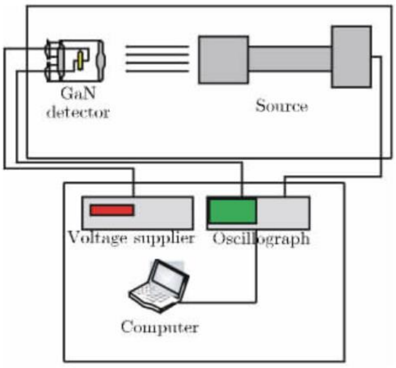

Fig. 10 Pulsed X-rays measurement layout.

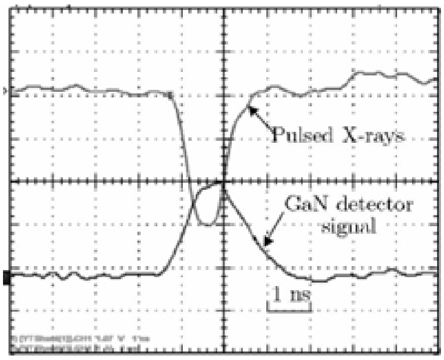

Fig. 11 Pulsed X-rays response results.

4 Conclusions

By theoretical simulation, experimental results and analysis above, it can be seen that the SI-GaN crystal has a very high resistivity which can reach $10^{14}\Omega\cdot$ cm, this crystal is a suitable material for hundred pA dark current detector. Under a certain bias, the deep-level defects of the detector material capture non-equilibrium carriers continuously during the process of irradiation, and the current signal becomes stable after the balance of carrier capture and escape form; The efficiency of charge collection increases with the bias getting higher. The charge collection efficiency is 40% with a super-fast response level of nanosecond when the bias is lower than 600V. Due to its high carrier mobility, it has a fast time response, which can be used for detecting pulse radiation in time-strength current mode, our GaN detector has an excellent performance which is expected to be an important tool for measuring parameters of the fusion detector, just like the ICF, Z–pinch.

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