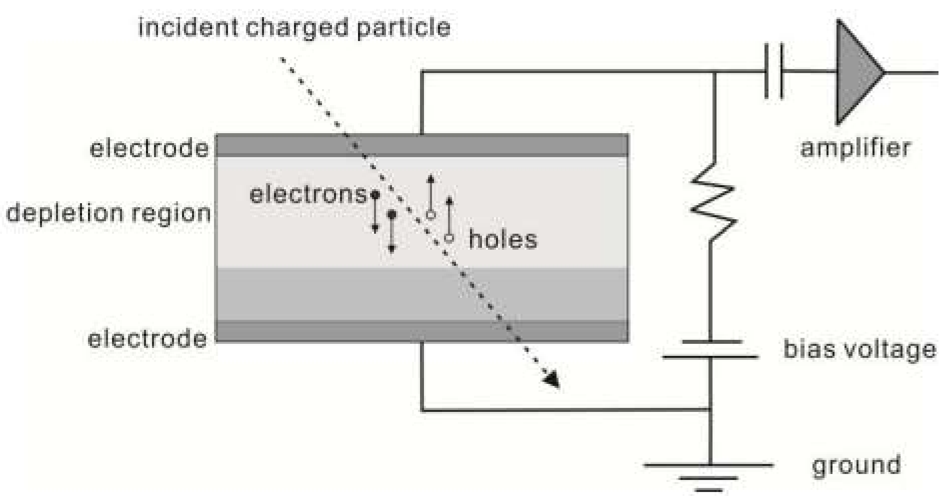
Evaluation of GaN as a Radiation Detection Material

remarkable properties, especially the wide band gap (3.39 eV), large dislocation density (N: 109 eV and Ga: 45 eV) and high thermal stability (Melting point: 2500 0C), GaN is now attracting considerable attention in application for nuclear radiation detections

only high quality GaN grown by MOCVD with carrier concentration on the orders of or less than 1016 cm-3 can be used for radiation detection.

Figure 1 presents a schematic diagram of a semiconductor detector, in which the semiconducting material is sandwiched between two metal electrodes. When a bias voltage is applied to the electrodes, the thickness of the depletion region inside the semiconductor will be increased. At this moment, if an incident charged particle enters the depletion region, electron-hole pairs (e-h) will be generated and drift toward the electrodes to form a signal. The strength of the signal, i.e., the number of e-h pairs generated, is proportional to the energy deposited by the charged particle in the depletion

region [21]. a



For a desired performance of semiconductor detectors, the properties of the

semiconductor material play the most important role. The following requirements need to

be met in order to fabricate a high quality detector [1]:

- 1, large band gap to ensure low leakage current, and the band gap should be larger than 0.14eV to prevent the generation of thermal carriers at room temperature;
- 2, the resistivity should be greater than 108 Ohm-cm to allow large bias voltage and thus to obtain a fast carrier drift velocity;
- 3, small e-h pair creation energy to maintain a high signal-to-noise ratio;
- 4, low dielectric constant to reduce white series noise [22];
- 5, high purity, homogeneous and single-crystal material to ensure high charge collection efficiency (CCE);
- 6, high mobility-lifetime product for charge carries to again ensure high CCE and also a good energy resolution. Specifically, for electrons and holes, this value should be better than 10**-2 and 10**-3 cm**2 V**-1, respectively;

An additional two features are preferred when working in high temperature and

hash radiation environments:

- 7, high threshold displacement energy to operate in harsh radiation environments or even in corrosive atmospheres;
- 8, high thermal conductivity to work at elevated temperatures

The depletion region is also named the “space charge region” or “active region”, in which the e-h pairs are generated upon receiving radiations.

the width of the depletion region will change according to the bias voltage which property is used to form Ohmic contact, as will be discussed later

During operations, leakage current will degrade the performance of the detector by introducing electronic noise. Two kinds of leakage exist in semiconductor detectors, as shown in Figure 5(a): Bulk leakage and surface leakage current. Bulk leakage current exists because of the finite conductivity of the semiconductor material; surface leakage current is generated due to the current path formed by the surface defect.

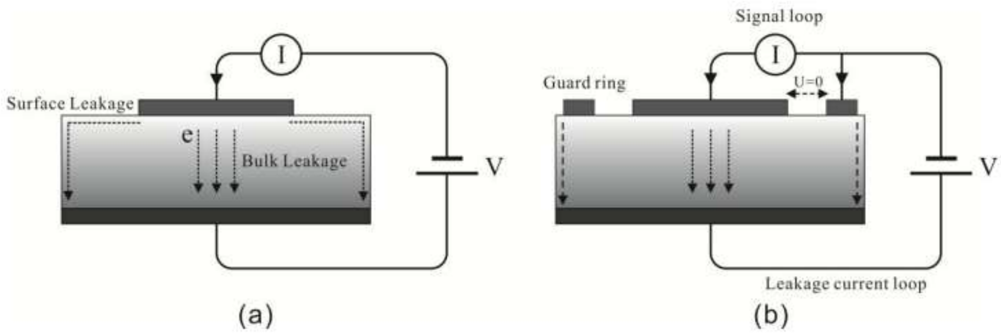


Figure 5. Leakage current (a) and guard ring structure (b)

At the level of 10-9 A, the surface leakage may be more significant than bulk leakage [21], and must thus be controlled to obtain a sufficient signal-to-noise ratio. Guard ring structure is introduced to minimize the surface leakage, as shown in Figure 5(b): by connecting both the Schottky contact and guard ring to the same reverse bias supply, there will be no potential drop between them and thus no surface leakage. Instead, the leakage current will be formed between the guard ring and Ohmic contact that will not affect the signal circuit loop [30].

--

Most semiconductor materials have very small neutron absorption cross sections, and thus neutron convertors are added into the detector for the purpose of making it neutron sensitive. There are three ways to add the convertors shown in Figure 7: coating, doping and super-lattice growing. Coating a convertor layer on top of the detector is one of the most widely employed methods, but the device may have a small CCE because half of the charge particles will escape from the top side of the device. Doping, either by diffusion or ion implantation, generates a significant amount of defects in the active region, which will degrade the performance of the detector. Super-lattice (SL) growing means the convertor and the semiconductor material are grown layer by layer to form the active region. This structure overcomes the drawbacks that existed in the former two methods. However, it needs advanced growing techniques and precise control conditions

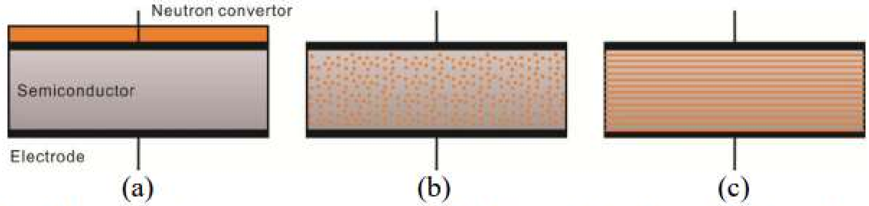


Figure 7. Adding of neutron convertors: (a) Thin-film coated device, (b) Doped device, (c) Super-lattice growing device

----

For semiconductor detectors, room temperature operations can only be achieved for band gaps above 1.4 eV. Thus, the wide band gap (WBG) semiconductors are defined as having a band gap higher than 1.4 eV

Figure 8 compares the band gap for different semiconductors [34]. GaN is a wide band gap semiconductor because it has direct band gap in the ultraviolet (UV) region with an energy of Eg = 3.42 eV [1]. AlN has the widest band-gap (6.2 eV) but with very low electron and hole motilities; SiC has almost the same electric properties as GaN but has a lower critical field than GaN.

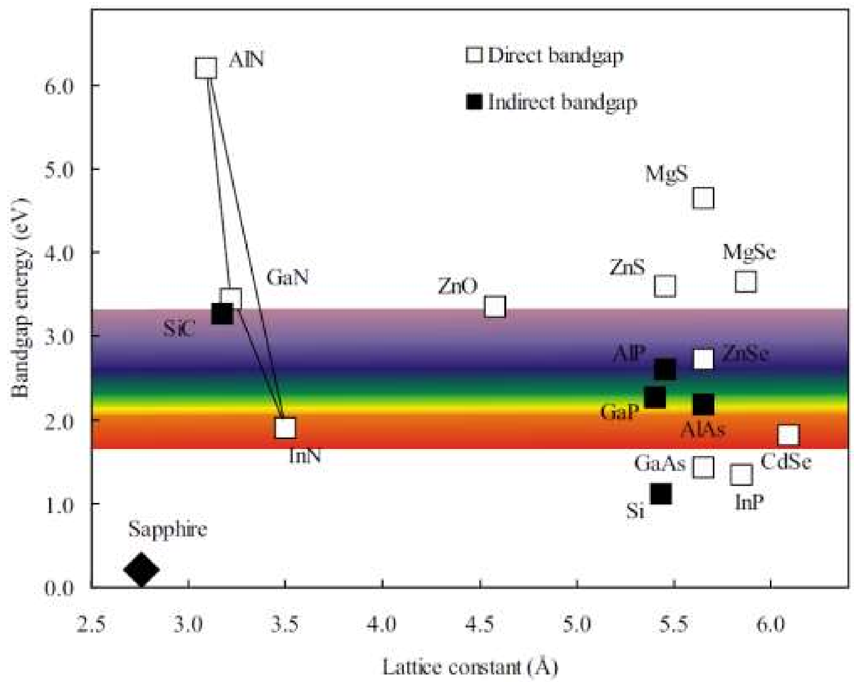


Figure 8. Band gap energy for various semiconductors [34]

For the double-Schottky contact structure, the electric field is perpendicular to the wafer surface and connects each Schottky contact with the buried high carrier concentration layer GaN [47]. For the mesa structure, etching process is employed to reach the buried layer in order to form Ohmic contact. Sandwich structure can be fabricated on freestanding GaN wafer, which has two advantages: low dislocation density and simple fabrication process. During fabrications, the Schottky contact is grown on Ga-side, while the backside Ohmic contact should be produced on N-side [48].In coplanar structure, both contacts are deposited on the front side and the pitch ranges from several to hundreds of micrometers. For both the sandwich and coplanar structures, two contacts can be Ohmic (photoconductive operation), Schottky (photovoltaic operation), and Schottky-Ohmic [49]. In this study, the mesa structure and the sandwich structure are applied

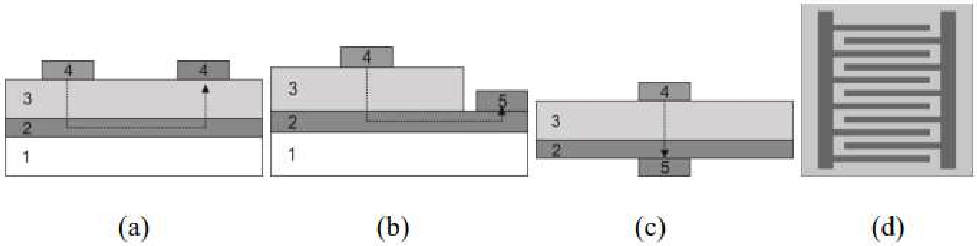


Figure 12. Possible detector structures based on Schottky diode: (a) Double-Schottky; (b) Mesa; (c) Sandwich; (d) coplanar; 1-Substrate, 2-high carrier concentration GaN, 3-Low carrier concentration GaN, 4-Schottky contact, 5-Ohmic contact

---

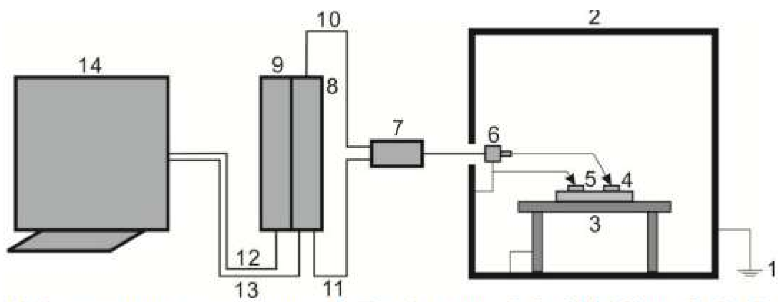


Figure 44. Alpha spectroscopy system: 1, Earth ground; 2, Shielding; 3, Probe station; 4, Ohmic contact; 5, Schottky Contact; 6, BNC cable; 7, Preamplifier; 8, CAEN N6724 Digitizer; 9, CAEN Power Supply; 10, Power supply to Preamplifier; 11, High voltage supply to detector; 12, Remote control of power supply; 13, Digitizer connect to computer; 14, Computer

The shielding of electromagnetic (EM) waves in the open air is necessary for an electronic circuit, especially when an amplifying process is involved. For our alpha spectroscopy system, two types of shielding methods are employed: Metal boxshielding and BNC wire shielding

The amplitude of an electromagnetic wave propagating through a conductor decays exponentially on a characteristic length scale named skin depth [12

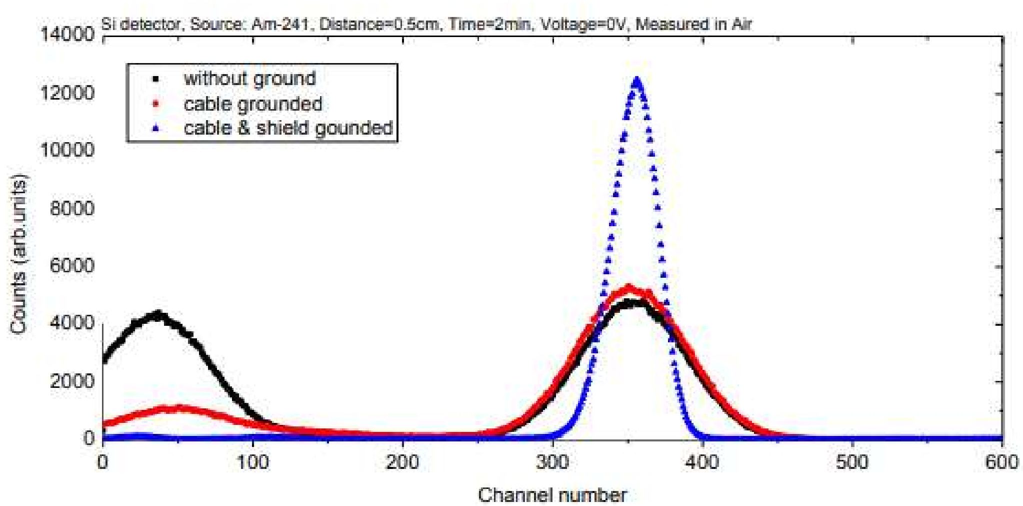
$$E(x,t) = E_0 e^{-x/d} \cos(\omega t - x/d) \quad (19)$$

In which E is the electric field strength of the EM, x the propagating depth to the conductor, ω the angular frequency of the EM given by $\omega = 2\pi f$, and d the skin depth that is given by

$$d = \sqrt{\frac{\rho}{\pi f \mu}} \quad (20)$$

Where ρ and μ are the resistivity and the absolute magnetic permeability of the conductor respectively. Based on this formula, the skin depth for different metals can be calculated, and the results of which are shown in Figure 45, from which we can see that steel is a very good material for shielding EM waves.

Besides shielding, the proper ground of the device also plays an important role for the alpha spectroscopy experiment. In our setup, the ground is fulfilled by connecting the shielding, the guard of the probe station, and the ground wire of the BNC cable to the metal sheet stick on the wall (earth ground). The effect of the ground can be clearly seen by sets of experiments keeping all the other parameters the same but with different ground methods (Figure 46): without any ground, ground the cable, and ground both the cable and the shielding box. From which we can see that the ground of both cable and shielding is necessary to significantly reduce the noise.



For the mesa structure disscussed later, there are some limitations when doing the alpha spectroscopy: First, the voltage should be less than 10 V in order to maintain a small leakage current. Second, based on the voltage supplied, only a low energy of about 100 keV can be deposited in the depletion region. Third, the distance between the source and detector is larger because the probe station is empoyed in the measurement in which two probes have to be put between them. Fourth, in order to maintain a low leakage curent, the active area of the detector is very small, in this case only about 0.09 mm2 (Schottky contact area) instead of 300 mm2 for the Si detecor. Thus, during the measurement, special care must be taken, especially regarding the optimization of the parameters for the control software

Charge Collection Efficiency

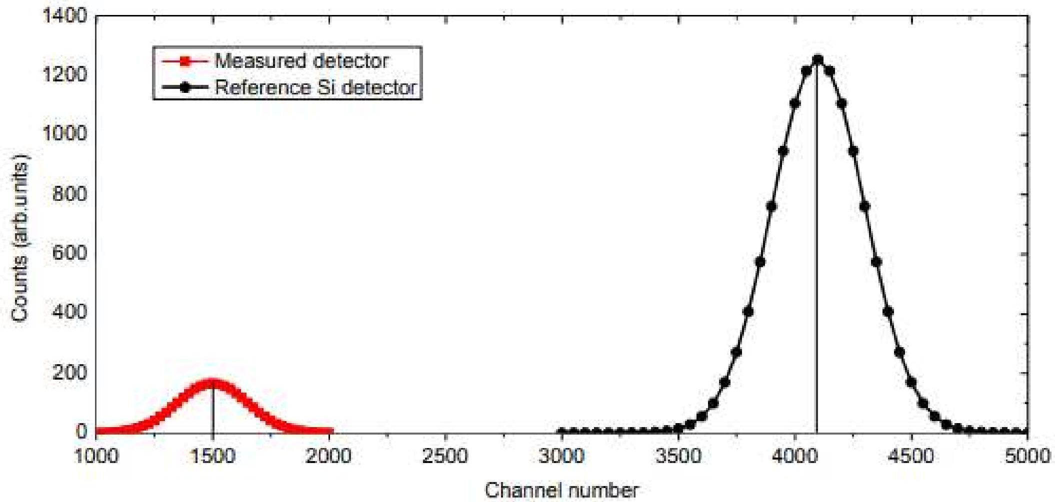
-Definition of CCE

The charge collection efficiency (CCE) of a detector is defined as the measured harge divided by the generated charge [13, 14]

$$CCE = \frac{Q_{meas}}{Q_{gen}} \quad (21)$$

When a charged particle enters the active region of the detector, its energy will be deposited in the detector and mainly cause two effects: one fraction of the energy is used for electronic stopping process to liberate e-h pairs, and one portion is used for nuclear stopping process to cause vibration of lattice atoms (also known as phonons). If all the generated electrons and holes are collected by the outer circuit, the CCE is said to be 100 %; otherwise, if some of them are trapped or recombined during transport process in the detector, then the CCE is less than 100 %

In view of the CCE measurement, detectors can be categorized into thick and thin detectors, which indicate whether or not the active region is thick enough to fully stop the incident charged particles. The CCE of a thick detector can be determined by comparing its alpha spectrum with the result of a silicon barrier detector, which is assumed to have a CCE of 100 % [14]. Figure 49 for instance illustrates this [13]: two alpha spectrums are generated by a Si detector and a test detector, respectively, after energy calibration if the channel number of 4100 corresponds to the energy of 4600 keV, and the channel number of 1500 corresponding to the energy of 1683 KeV, then the CCE of the tested detector is approximately 1683/4600=37 %



For thin detectors, the thickness of the active region is smaller than the project range of the charged particle. Thus, only a portion of its energy is deposited in the detector. In this case, the CCE can be estimated by comparing the experimental result with the simulation result generated from SRIM code.
