Analysis of CSNS neutron-induced displacement damage effects on top illumination planar InGaAs p-i-n photodetectors

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A R T I C L E  I N F O

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- InGaAs p-i-n photodetector
- Displacement damage
- CSNS
- Bias condition
- Irradiation flux

A B S T R A C T

The displacement damage effects on indium gallium arsenide (InGaAs) p-i-n photodetectors induced by neutron at China Spallation Neutron Source (CSNS) are analyzed. The irradiation fluence range from $1.0 \times 10^{11}$ to $3.6 \times 10^{13}$ cm$^{-2}$. The InGaAs p-i-n photodetector under investigation was fabricated with top illumination structure. The forward and reverse bias current–voltage (I–V) under the dark environment is measured before and after neutron radiation in the room environment. Experiment results for different bias conditions and different irradiation flux were compared. The mechanism of displacement damage effects on the I–V characters of InGaAs p-i-n photodetectors are analyzed combined with TCAD simulation. The annealing effects on InGaAs p-i-n photodetectors are also investigated.

1. Introduction

Indium gallium arsenide (InGaAs) photodiodes have been widely used in the scientific field, such as inter-satellite optical communications, satellite remote sensing, and optical data links at high energy physics experiments (for example, the Compact Muon Solenoid experiment at CERN Large Hadron Collider) [1–5]. However, when used in these field, InGaAs photodiodes would be damaged by particles or rays, which would lead to parameter degradation or even functional failure. The main radiation damage induced by particles or rays of InGaAs photodiodes is ionizing effects and displacement damage (DD) effects. The mechanisms induced by the radiation damage need to be understood.

Many studies are carried out to analyze the radiation effects on InGaAs photodiodes. For example, H. Ohyama et al. [6–9] have investigated the high energy particles (such as 220 MeV carbon, 20 MeV alpha rays, fast 1 MeV neutrons, 2 MeV electrons) radiation effects on the In$_{53}$Ga$_{47}$As p-i-n photodiodes. The damage coefficient at a fixed fluence for the dark current and photo-current are present, and the deep levels of the traps induced by particle irradiation were measured by using deep level transient spectroscopy (DLTS). O. Gilard et al. [10] have studied the displacement damage factor of the InGaAs photodiodes induced by various particles with different energy. L. Olantera et al. [11] have presented the 24 GeV/c proton and 20 MeV neutron radiation effects on the high-speed InGaAs photodiodes. The radiation effects on responsivity, dark current and capacitance of InGaAs photodiodes are analyzed. However, fewer studies have focused on the impact of bias conditions and irradiation flux on performance degradation in InGaAs photodiodes, especially for spallation neutron. Impact of bias conditions and irradiation flux on radiation effects of-in InGaAs photodiodes is important to estimate the life of the device under the radiation environment.

China Spallation Neutron Source (CSNS) facility provides a large scientific platform [12]. The back-streaming white neutrons (Back-n) from a spallation target through the proton beam line in CSNS facility has a very wide neutron energy spectrum, which can be used to perform the displacement damage effect induced by neutron radiation [13]. Besides, InGaAs photodiodes could be used in the CSNS to receive the digital timing and control signals transmitted. The degradation of InGaAs photodiodes induced by neutron irradiation needs to be understood.

When the neutron incident on the InGaAs photodetectors, it may knock on atoms and produce vacancies and interstitials. A vacancy and a nearby interstitial are also called a Frenkel pair. Those defects will reorder to form more stable configurations, which may give rise to energy levels in the bandgap. The energy levels in the bandgap would have great effects on the dark current performance of the InGaAs photodetectors. In order to analyze the effect on the dark current due to the defects produced by neutron irradiation in the InGaAs photodetectors, simulations with technology computer aided design (TCAD) tool have been carried out.

In this paper, the displacement damage effects on InGaAs p-i-n photodetectors are investigated. The irradiation experiments are carried

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out at Back-n of CSNS with different bias conditions and irradiation flux. The forward and reverse bias current–voltage (I–V) under the dark environment is measured before and after neutron radiation in the room environment. The annealing effects on InGaAs p-i-n photodetectors after neutron radiation also studied. The mechanism of displacement damage effects on InGaAs p-i-n photodetectors is analyzed combined with TCAD simulation.

2. Experimental details

The experiment of displacement radiation effects in InGaAs p-i-n photodiodes has been carried out at the Back-n source in CSNS. The neutron energy is ranging from 1 eV to 200 MeV (Fig. 1). High flux neutrons are produced by a proton beam of 1.6 GeV and 25 Hz in repetition rate impinging a thick tungsten target with 50 kW in our experiment. The temperature in the laboratory is about 20 °C controlled by air conditioning. The InGaAs p-i-n photodiodes after neutron radiation with different fluence have been obtained with the flux of 3.5 × 10^6 n/cm²/s while the irradiation fluence of 36 × 10^11 n/cm² has been achieved with the flux of 8.1 × 10^6 n/cm²/s. All of the devices are open-circuited. The linear fitting is used to calculate the Kd of the InGaAs photodetectors after Back-n radiation.

Table 1 Irradiation test conditions.

<table>
<thead>
<tr>
<th>Simple number</th>
<th>Fluence</th>
<th>Flux</th>
<th>Bias condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10^11 n/cm²</td>
<td>3.5 × 10^6 n/cm²/s</td>
<td>Unbiased</td>
</tr>
<tr>
<td>2</td>
<td>5.0 × 10^11 n/cm²</td>
<td>3.5 × 10^6 n/cm²/s</td>
<td>Unbiased</td>
</tr>
<tr>
<td>3</td>
<td>3.0 × 10^11 n/cm²</td>
<td>3.5 × 10^6 n/cm²/s</td>
<td>Unbiased</td>
</tr>
<tr>
<td>4</td>
<td>1.0 × 10^11 n/cm²</td>
<td>3.5 × 10^6 n/cm²/s</td>
<td>Unbiased</td>
</tr>
</tbody>
</table>

3. Results and discussion

3.1. Experiment results

The reverse dark current is one of the most important parameters of the InGaAs photodetector and its sensitivity to the displacement damage effects. After neutron radiation, the dark reverse current could increase obviously. As mentioned in ref [6], there is a linear relationship between reverse dark current and neutron irradiation fluence:

\[
I_d(\Phi) = I_d(0) + K_d\Phi
\]

where \(I_d(\Phi)\) and \(I_d(0)\) is the reverse dark current after neutron radiation, \(K_d\) is the damage coefficient of reverse dark current, and \(\Phi\) is the neutron irradiation fluence. The reverse dark current is one of the most important parameters of the InGaAs photodetector and its sensitivity to the displacement damage effects. After neutron radiation, the dark reverse current could increase obviously. As mentioned in ref [6], there is a linear relationship between reverse dark current and neutron irradiation fluence:

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where \(I_d(\Phi)\) and \(I_d(0)\) is the reverse dark current after neutron radiation, \(K_d\) is the damage coefficient of reverse dark current, and \(\Phi\) is the neutron irradiation fluence. Fig. 4 shows the reverse current of InGaAs photodetectors before and after neutron radiation with different fluence and flux. The irradiation fluences ranging from 1–10 × 10^11 n/cm² have been obtained with the flux of 3.5 × 10^6 n/cm²/s while the irradiation fluence of 36 × 10^11 n/cm² has been achieved with the flux of 8.1 × 10^6 n/cm²/s. All of the devices are open-circuited. The linear fitting is used to calculate the \(K_d\) of the InGaAs photodetectors after Back-n radiation.
Fig. 4. The reverse current of InGaAs photodetectors before and after neutron radiation with different fluence and flux.

Fig. 5. The reverse dark curves of InGaAs photodetectors before and after neutron irradiation with different bias conditions.

<table>
<thead>
<tr>
<th>Reverse voltage (V)</th>
<th>Goodness of fit</th>
<th>$K_d$ (A cm$^{-2}$/neutron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.996</td>
<td>4.17x10$^{-22}$</td>
</tr>
<tr>
<td>3.0</td>
<td>0.998</td>
<td>7.85x10$^{-22}$</td>
</tr>
<tr>
<td>5.0</td>
<td>0.997</td>
<td>1.29x10$^{-21}$</td>
</tr>
<tr>
<td>7.0</td>
<td>0.996</td>
<td>1.98x10$^{-21}$</td>
</tr>
<tr>
<td>10.0</td>
<td>0.995</td>
<td>3.50x10$^{-21}$</td>
</tr>
</tbody>
</table>

Table 2
The damage coefficient of reverse dark current for different reverse voltage.

and +0.5 V during irradiation. This suggests that carrier motion and the electric field would affect the defects induced by neutron radiation. Fig. 6. shows the reverse dark current of the photodetector which is irradiated by neutron with the fluence 3.6x10$^{12}$ n/cm$^2$ under unbiased condition versus annealing time. From Fig. 6 one can see that the reverse dark current at −5 V after 5 months of long-term annealing recovered nearly 29.5% but its less than pre-irradiation value.

Fig. 7(a) shows the forward current of InGaAs photodetectors before and after neutron radiation with different fluence and flux, and Fig. 7(b) shows the forward current of InGaAs photodetectors versus the irradiation fluence at different voltage. Fig. 8(a) shows the forward current of InGaAs photodetectors before and after neutron irradiation with different bias condition and Fig. 8(b) shows the forward current of InGaAs photodetectors versus the irradiation bias conditions at different voltage. From Fig. 7 and Fig. 8 one can see that the forward
Fig. 7. The forward current of InGaAs photodetectors before and after neutron radiation with different fluence and flux.

Fig. 8. The forward current of InGaAs photodetectors before and after neutron radiation with different bias conditions.

current increases as a function of the neutron fluence with a bias voltage in the range 0–0.6 V. In addition, the device biased at +0.5 V during irradiation is the severest condition to evaluate the displacement damage effects on the InGaAs photodetector, but it’s not obviously when compared with the device biased at −0.5 V during irradiation.

3.2. Simulation results

The simplified InGaAs photodetector structure models are established according to the real parameters of the device under test as shown in Fig. 9. The Shockley-Read-Hall (SRH) recombination, Optical recombination (OPTR), Auger recombination are considered. The bandgap of In$_{0.53}$Ga$_{0.47}$As is 0.75 eV and the bandgap of InP is 1.35 eV at 300 K. The radiation-induced traps are introduced in the absorption layer uniformly. The level and density of radiation-induced traps are mainly relevant to the type, energy, and fluence of the incident particle, the doping concentration, and the irradiation temperature. In this work, a deep level trap centers of $E_c$−0.29 (eV) with equal electron and hole capture cross-section (1×10$^{-15}$ cm$^{-2}$) are used [15]. The density of traps is ranging from 1×10$^{13}$–10$^{17}$ cm$^{-3}$.

Fig. 10 shows the simulated reverse dark current versus trap density. From Fig. 10 one can see that the reverse dark current increases, increasing the trap density. The degradation of reverse dark current becomes more severe and it increases linearly with the trap density when the trap density is more than 10$^{15}$ cm$^{-3}$, which is similar to the result in reference [15]. Fig. 11 gives the simulated forward current after irradiation. The results are in agreement with the results of the experiment as shown in Fig. 8. Fig. 12 shows the electric field profile distribution in InGaAs photodiode before and after irradiation (traps density = 10$^{17}$ cm$^{-3}$). From Fig. 12 one can see that traps in the absorption layer have great an effect on the electric field. The bulk defects located inside the absorption region and act as classical SRH generation centers and produce electrons and holes. The lifetimes and carrier mobilities of electron and hole would be affected by the electric field. The high electric field would make the electrons and holes more...
3.3. Discussion

The bias conditions during irradiation would have great effects on the displacement damage effect in InGaAs p-i-n photodetector. Many works have been carried out to analyze the impact of bias conditions on performance degradation in devices such as silicon-germanium (SiGe) heterojunction bipolar transistors (HBTs) [16], multi-quantum well laser diode [17]. The free charge carrier can enhance the defect ordering and then the annealing rate, and then enhances the annealing rate. It’s also called the injection annealing. As for the multi-quantum well laser diode, the open-circuited is the severest condition when compared with other conditions [17], which is different from the results in our experiment. Two possible reasons may explain this phenomenon. One is that the working principle of these devices is different. The InGaAs photodetector is sensitive to the photons ranging from 900 nm to 1700 nm. In our experiments, the sensitive area of the InGaAs photodetectors is not shaded. This means that the photons can enter the device and reaching the absorption region where carriers are generated.

The carriers would be accumulated in the absorption region and would have great effects on the annealing of defects. The other is that the electric field may have an effect on the annealing of defects, which will be investigated in the future.

4. Summary and conclusion

The displacement damage effects on InGaAs p-i-n photodetectors induced by Bank-n at CSNS have been investigated. The forward and reverse dark bias current increases significantly induced by displacement damage. The displacement damage factor induced by Bank-n neutron is about 1.29×10^{-21} (A cm^{-2})/n of this kind of InGaAs p-i-n photodetectors at −5 V bias voltage. The annealing effect is also observed. The SRH generation plays an important role in reverse dark current and forward dark current (lower voltage) after neutron irradiation.

In future works, more experiments and simulations will be carried out to analyze the bias condition effects on the InGaAs p-i-n photodetectors. The level, density, cross-section of the defects induced by displacement damage would be characterized by DLTS. The radiation effects on the electric field, carrier concentration, and performance of the InGaAs p-i-n photodetector would be investigated by combining with TCAD simulation. The mechanism of the displacement damage effects will also be studied.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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