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Effect of proton irradiation on extended wavelength $In_{0.83}Ga_{0.17}As$ infrared detector

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HIGHLIGHTS

- The performance of $In_{0.83}Ga_{0.17}As$ detector degraded after proton irradiation.
- The proton irradiation mainly increases the shunt component of dark current.
- The proton irradiation increases all components of low frequency noise.

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ABSTRACT

Extended wavelength $In_{0.83}Ga_{0.17}As$ infrared detectors have been irradiated with 2 MeV proton with a fluence of $1 \times 10^{15}\ cm^{-2}$. Dark current–voltage characteristics, low frequency noise (LFN) and response spectra were measured before and after irradiation at room temperature (RT) to investigate the irradiation effect. The results showed that dark current and LFN increased after irradiation, and the responsivity decreased. The performance degeneration of detectors is generally related to the defects originated from the displacement effect of irradiation. The analysis of dark current mechanisms indicates that the irradiation mainly results in the increase of shunt component. The degeneration of LFN is attributed to the increase of all noise components, i.e. $1/f$ noise, g–r noise and white noise. The annealing behaviors of dark currents were observed at RT. The dark currents decreased by about 17% on average by the 19th hour and then hardly recovered by the 225th hour after irradiation. The InGaAs/InAlAs multilayer epitaxial material used to fabricate the detector was also irradiated. The Photoluminescence (PL) measurements at 77 K showed that PL intensity of InGaAs layer decreased much greater than that of InAlAs layer after irradiation.

1. Introduction

The compound $In_{0.53}Ga_{0.47}As$ material with cutoff wavelength of 1.7 μm is lattice-matched to InP substrate. The cutoff wavelength of $In_{1-x}Ga_xAs$ material can be extended to 2.6 μm by adjusting the composition ratio of In fraction to 0.83. $In_{1-x}Ga_xAs$ material covers the short wave infrared (SWIR) band of 1–3 μm, which contains some absorption bands for O—H, C—H, C—O, C=O and N—H [1,2]. The particular spectroscopic features enable InGaAs detectors to play an important role in space remote sensing, night vision, gas detection, environmental monitoring, etc [2–4].

InGaAs detectors have widely served on satellites, e.g. SPOT 4 (France), Envisat (ESA), NOAA-18 (America), etc. There are abundant protons, electrons and gamma rays in the space environment [5,6]. Due to ionization and displacement effect, the space radiation can induce temporary damage and permanent damage in the detectors on satellite. The "unstable" dark current level periodically switching between several discrete levels has been observed on SPOT 4 satellite using InGaAs detectors [7]. Q.L. Kleipool reported that 50 pixels of 1024 × 1 linear InGaAs detectors on the Envisat satellite broke down per year because of proton irradiation [4].

To ensure the reliable application of InGaAs infrared detectors in the space, it is essential to investigate the effect of particle irradiation on the performances of detectors on the ground. The irradiation inducing degeneration of the performances of lattice-matched InGaAs detector has been studied in detail by

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many researchers [7–11]. Extended wavelength InGaAs detectors attracted much attention in recent decades [2,12–15]. However, the investigations on their irradiation effect are still far from enough. The published few reports have not observed significant change with irradiation yet [4,16]. It might be due to the lower irradiation fluence.

In this paper, we present the effect of 2 MeV proton irradiation on the extended wavelength $In_{0.83}Ga_{0.17}As$ detectors. Dark current–voltage (Dark I–V) characteristics, low frequency noise (LFN) and response spectra were measured to characterize the degeneration of the detectors. The variations of the components of dark current and low frequency noise were analyzed. The materials used to fabricate the detectors were also irradiated and photoluminescence (PL) spectra were conducted to represent the change. Besides, we observed the recovery of the dark currents of the detectors.

2. Experiment details

The material samples M1 and M2 with InAlAs /$In_{0.83}Ga_{0.17}As$/InAlAs p–i–n epitaxial structure were grown on semi-insulating InP substrate by Gas Source Molecular Beam Epitaxy (GSMBE) [14,17]. The epitaxial structure consisted of a 1.9 μm N-InAlAs buffer layer with a doping concentration of about 3×10^{18} cm^{-3}, a 1.5 μm n-$In_{0.83}Ga_{0.17}As$ absorption layer (3×10^{16} cm^{-3}) and a 0.6 μm P-InAlAs cap layer (2×10^{18} cm^{-3}). The device sample D1 and D2 were fabricated on the epitaxial structure by a set of processes. Firstly, mesa structure was formed by Inductively Coupled Plasma etching. After the mesa isolation, SiN_x passivation layers were grown by inductively coupled plasma chemical vapor deposition (ICPCVD). Then, Ti/Pt/Au ohmic contact was deposited by an e-beam evaporation system and annealing process was performed in a rapid thermal annealing apparatus. At last, Cr/Au film was spluttered on the contact pads. Each device sample contains eight photodiode elements with photosensitive areas of 20×20, 30×30, 50×50, 75×75, 100×100, 120×120, 150×150, and 200×200 μm^2, respectively.

Samples M1 and D1 were irradiated with 2 MeV proton with a fluence of 1×10^{15} cm^{-2} at NEC 9SDH-2 2×3 MV tandem accelerator. No bias voltage was applied to the sample D1 during irradiation. Sample M2 and D2 acted as contrasts. Before and after irradiation, dark I–V characteristics of sample D1 were measured by Agilent B 1500ASemiconductor Device Analyzer. LFN spectra of sample D1 were recorded by Agilent HP35670A dynamic signal analyzer. Response spectra of samples D1 and D2 were carried out by Nicolet Magna Fourier transform infrared (FTIR) spectrometer. All measurements for samples D1 and D2 were performed at room temperature (RT). PL spectra of samples M1 and M2 were measured by Bruker 80v FTIR spectrometer equipped with InGaAs and HgCdTe detectors at 77 K. The annealing behavior of dark current was observed at RT after irradiation.

3. Results and discussion

Fig. 1 illustrates the pre- and post-irradiation (pre- and post-irrad) dark current of sample D1. The measured pre- and post-irrad dark I–V characteristics (point) of the diode with area of 100×100 μm^2 in the sample D1 are shown in Fig. 1(a). The current at −0.1 V are extracted from I–V characteristics and normalized to area for all diodes. The current density with perimeter/area (P/A) is shown in Fig. 1(b). The irradiation induces the current to increase by 2–5 times at the same voltage in the test range. The current densities are both next to independent on P/A before and after irradiation. It indicates that the irradiation mainly results in bulk damage in the sample D1.

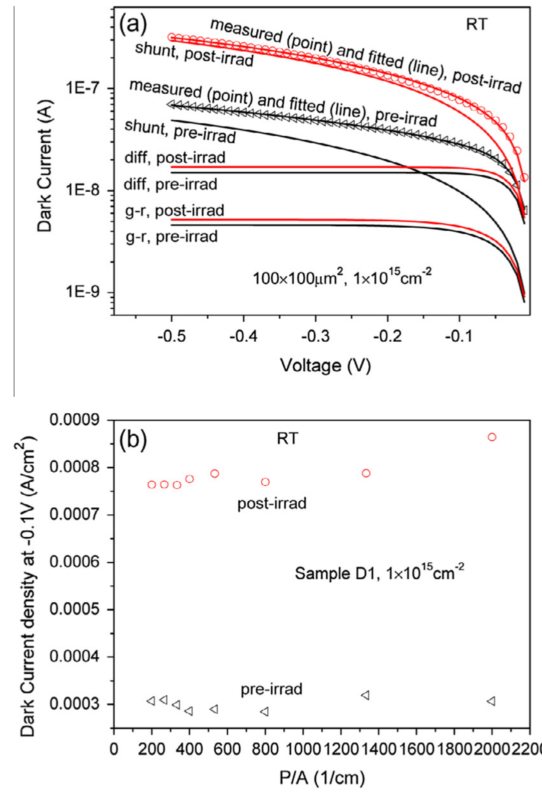

Fig. 1. Pre- and post-irrad dark current of sample D1. (a) Measured dark I–V characteristics (point) and fitted curves (line) of the diode with area of 100×100 μm^2. (b) Dark current density at −0.1 V with P/A.

Diffusion (diff), generation–recombination (g–r) and shunt currents are major components of current in $In_{0.83}Ga_{0.17}As$ diode at RT [15]. In order to identify the effect of irradiation on the current mechanisms, the measured data are fitted according to the well-known expressions for the three current components. The fitted curves (line) are also shown in Fig. 1(a). The post-irrad shunt component is much higher compared to the pre-irrad. The increase of diff and g–r components with irradiation is much less compared with shunt component.

The basic effects of high energy particle irradiation on semiconductor material consist of ionization effect and displacement effect. Ionization effect induces a lot of non-equilibrium carriers. These non-equilibrium carriers perturb the electrical parameters of material transiently and will recombinant completely in a short time after irradiation. Displacement effect induces defects at internal, the surface and interface of material. These defects will persist for a long time or permanently after irradiation and affect the performance of semiconductor device. In this work, the pre-irrad shunt current is known to be related with dislocations originating from lattice mismatch [15]. The radiation-induced defects could sever as leakage channels and increase the shunt component. However, the radiation-induced defects only have a little contribution to the diff and g–r components.

Fig. 2 shows the measured pre- and post-irrad noise current spectra (point) of the diode (100×100 μm^2) in the sample D1 at −0.1 V. The LFN of the diode increases a lot after irradiation. The LFN of an electron device consists of $1/f$ noise, g–r noise and white noise [18], i.e.

$$S(f) = \frac{A}{f^{\gamma}} + \sum_{i=1}^{N} \frac{B}{1 + (f/f_{0i})^2} + C \quad (1)$$

where A, B and C are the amplitudes of each noise component, γ is the exponential factor of $1/f$ noise and usually between 0.8 and 1.2,