Solid-State Electronics 109 (2015) 52–57

Contents lists available at ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Investigation of proton irradiation effects on InP/InGaAs double heterojunction bipolar transistors

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ARTICLE INFO

Article history:
Received 5 September 2014
Received in revised form 3 February 2015
Accepted 4 March 2015
Available online 1 April 2015

Keywords:
Proton irradiation
Heterojunction bipolar transistors
InP/InGaAs
DC characteristics

ABSTRACT

In this article, 3 MeV proton irradiation-induced degradation in InP/InGaAs double heterojunction bipolar transistors (DHBTs) is studied, the fluence up to 5×10^{12} protons/cm^2, meanwhile 10 MeV proton irradiation is investigated in order to compare the differences induced by different proton energy irradiation. The devices exhibit good tolerance up to 5×10^{11} protons/cm^2. The concentration of vacancies at different proton fluences can be calculated from SRIM. Being donor-like defects, the In and Ga vacancies act as compensation center while As vacancy acts as an acceptor-like defect. Adding the vacancies model into Sentaurus device simulator, simulation results match well with the trends of measured data.

1. Introduction

Heterojunction bipolar transistors with lattice matched to InP substrates are of increasing interest. InP/InGaAs HBTs have higher electron mobility in the InGaAs base layer, higher velocity overshoot in the collector and lower surface recombination velocity, making them suitable for high-speed analog and digital applications [1].

Space-borne applications not only require high speed, lower power consume, wide frequency broadband, but also radiation tolerant. Hence, the reliability of the devices in radiation environment is an important issue. The effects of neutron, electron, and gamma irradiation on InP/InGaAs HBT have been investigated for a long time [2–4]. Such studies are useful for providing good understanding of the radiation damage process and improving predictive capabilities for assessing device performance in a radiation environment. It is well-known that protons are of special interest in space applications as these are one of the most common particles encountered in the Earth environment [5].

Most irradiation studies on InP/InGaAs HBTs reported so far have mainly focused on the electrical characteristics changes before and after irradiation. However, to our knowledge, there are not many papers published on modeling the electrical characteristics of the irradiated InP/InGaAs HBTs [6].

In this paper, the results of the dc characteristics of InP/InGaAs DHBTs subjected to different fluences of proton irradiation are reported. The experimental details are presented in Section 2. The results are then discussed in Section 3 and the simulation is presented in Section 4. Section 5 is the conclusion.

2. Experiment

The InP/InGaAs DHBTs with $1.0 \times 15\ \mu m^2$ emitter area used in this study were fabricated at Institute of Microelectronics. The DHBT structure was grown by gas source molecular beam epitaxy (GSMBE) on a semi-insulating InP substrate. The schematic structure is shown in Fig. 1, and the detail of structure can be found in Ref. [7]. Both the emitter and collector contacts were deposited using Ti/Pt/Au while the base contact using Pt/Ti/Pt/Au.

The InP/InGaAs DHBTs were irradiated with 3 MeV protons at the Peking University proton accelerator EN2 × 6. The proton fluences are 10^{11}, 5×10^{11}, 10^{12} and 5×10^{12} protons/cm^2 respectively, and the beam density is 0.027 nA/cm^2 s. That is to say, the irradiation time is 10 min, 50 min, 100 min and 500 min respectively, according to the proton fluences listed above. Three devices from the same wafer were used for each experiment to check the variations. All of them showed the similar behavior before and after irradiation. Proton produces both ionization and displacement damage. The ionization damage mainly contributes to the generation of electron–hole pairs, and short-term currents

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http://dx.doi.org/10.1016/j.sse.2015.03.008

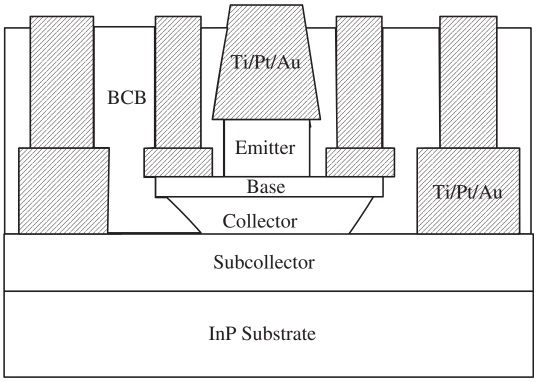

Fig. 1. Schematic cross-section of InGaAs/InP DHBT.

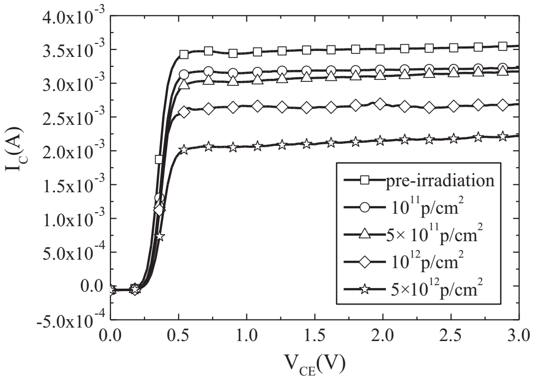

Fig. 3. Collector I_C–V_{CE} characteristics at base current of 60 μA after different levels of exposure.

produced. However, the measurement in our work is not on-line and the device terminals were left in a floating condition. Delay time between irradiation and remote testing was about one hour and the recombination of electron–hole pairs occurs fast. Therefore, the displacement damage plays a dominant role in the irradiation effect. The on-wafer DC performance of the samples were characterized by an HP4142 semiconductor parameter analyzer at room temperature before and after irradiation.

3. DC results and discussion

The common-emitter collector current–voltage (I_C–V_{CE}) characteristics of the samples before and after proton irradiation at fluence of 5×10^{12} protons/cm^2 are shown in Fig. 2. Fig. 2 reveals the following prominent degradation effects:

1. Reduction of collector current (I_C) for a fixed base current (I_{BE}).
2. Increase of collector–emitter knee voltage.

The changes in characteristics at different 3 MeV proton fluences are shown in Fig. 3 at a base current of 60 μA. From Fig. 3, it is seen that the collector current decreases after irradiation. The reduction in the collector current implies a degradation of the common emitter current gain.

To understand the physical mechanisms for the degradation of current gain, forward-mode Gummel plot (with V_{BC} is fixed at zero) were performed at different fluence levels. The experiment results are presented in Fig. 4(a) and (b), respectively. At low V_{BE} (<0.7 V) the base current increases with irradiation. As can be seen from them, the larger base current is caused for the bigger irradiation fluence, therefore leading to current gain drop down. The increase of I_{BE} at low V_{BE} is generally due to increased recombination in the base-emitter space-charge region and at its periphery after irradiation [8].

The proton irradiation damage mechanism in InGaAs can be clearly interpreted by SRIM [9]. Energetic protons transfer a part of their kinetic energy to the In, Ga and As atoms through ion–solid interactions, namely, non-ionizing energy loss (NIEL). This results that atoms break away from their lattice sites and vacancies are created. In the case of InP/InGaAs HBTs, the main areas are the BE junction and the neutral base region. Hence, more attention is paid to 40 nm InP emitter layer and 65 nm InGaAs base layer. The detailed thicknesses of the device layer and the displacement energy of In, P, Ga, and As atoms are described in the input document of SRIM. According to the number of vacancies created in the given depth after energetic proton incidence, the density of vacancies at different proton fluencies are calculated. Fig. 5 shows the vacancy concentrations created in the InGaAs base layer versus 3 MeV proton fluences. As the fluence of the incident proton increases, the vacancy concentrations increase linearly.

In order to understand the relation of current degradation with the irradiation-induced damage, the variation of ideality factor of base current I_{BE} has been investigated. The ideality factor is extracted from the small current regime of the Gummel plot as shown in Fig. 6. It is obvious that the ideality factor rises from initial value of 2.21 to a final value of 2.86 after higher fluences. In general, the ideality factor close to 2 in small current range is mainly due to the space charge region recombination around base region and its periphery, but for the case of bigger than 2 of ideality factor, it may have the defect energy states assisted tunneling current involved. So there is a reason to believe that the increased ideality factor with enhanced proton fluence irradiation is due to the pre-existing or radiation induced trap sites [10]. This means that some defects exist in the devices before irradiation due to material growth or device process.

Annealing, both at elevated and at room temperatures, have been found to ameliorate some of the damages. The forward mode results show significant recovery, in both the proton and gamma irradiated SiGe HBTs samples [11]. There is the same case in our devices after three month room temperature annealing, showing in Fig. 7. The current change of the devices can be explained by under the framework of electron trapping and de-trapping from the near interface traps [12]. The device, which was kept under room temperature storage after proton irradiation for three months, shows base current recovery comparing with that of irradiation.

Devices of different areas were irradiated to understand if volume effects or perimeter effects are dominant. The transistors with different emitter sizes are presented by T1, T2, T3, T4, T5, listing in

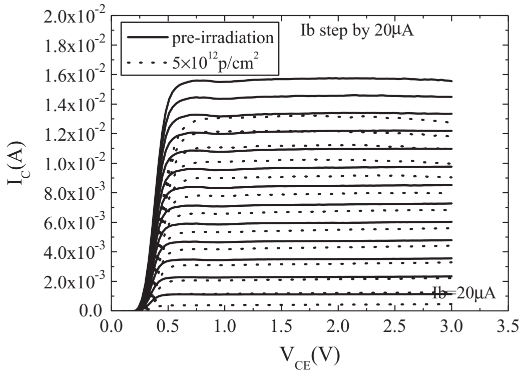

Fig. 2. Collector I_C–V_{CE} characteristics of the unexposed device and after 5×10^{12} protons/cm^2 irradiation.