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Low energy proton irradiation induced interface defects on Pd/n-GaAs Schottky diodes and its characteristics

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Abstract

The effect of low energy proton irradiation induced damage on the near interface of the Pd/n-GaAs Schottky Barrier Diodes (SBDs) has been studied using *I-V* and *C-V* characteristics. The reverse leakage current increases with irradiation fluence. Annealing the irradiated SBDs helps to anneal out the irradiation induced defects. Annealing mechanism of the defects in the irradiated SBDs with different fluences are discussed. The reverse leakage current is more for the CONTROL SBDs annealed at 673 K, which is attributed to the formation of a thin heavily doped GaAs layer at the interface. A decrease in the capacitance has been observed in the irradiated and annealed SBDs for the fluences 1×10^{14}, 1×10^{15} and 1×10^{16} p cm^{-2}. For higher incident particle fluences (1×10^{15} and 1×10^{16} p cm^{-2}) a slight increase in the capacitance has been observed compared to 1×10^{14} p cm^{-2} fluence. © 1998 Elsevier Science B.V.

Keywords: GaAs; Proton irradiation; Metal–semiconductor; *I–V* measurement; *I–V–T* measurement; *C–V* measurement

1. Introduction

Schottky Barrier Diodes (SBDs) are important components for applications involving high speed digital and microwave integrated circuits for data and signal processing in communication systems. In space environment, these devices are exposed to electron, neutron, proton, and alpha particle irradiation with energies in the range of 1 keV to hundreds of MeV. High energy particles penetrate the interface and cause damage deep below the interface. Low energy particles cause severe lattice damage in the form of vacancies, interstitials and defect complexes at the near interface of the device [1–6]. Hence, it is very much essential to evaluate the effect of irradiation and identify the degradation mechanism to understand the failure mechanisms.

Among the irradiation sources, protons are mostly used for defect studies as a 1 MeV proton

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can transfer a maximum energy of 5.4% of its initial energy to a gallium or an arsenic atom as compared to the relatively low transfer (0.006%) by 1 MeV electron. 1 MeV protons of 8×10^{10} cm^{-2} or 7.3 MeV electrons of 8×10^{13} cm^{-2} irradiated on GaAs cause 18 times more damage than 2 Mrad of ^{60}Co gamma [1]. In this article, we report the change in the electrical properties (*I–V* and *C–V*) due to low energy proton irradiation at the near interface of the Pd/n-GaAs SBDs.

2. Experimental procedure

The SBDs were fabricated using LEC grown (1 0 0) oriented silicon doped n-GaAs (carrier concentration 4×10^{17} cm^{-3}) substrates [6]. The chemo-mechanically polished substrate surface was cleaned in organic solvents (TCE, acetone and methanol) and etched in HCl:H_2O. Ohmic contact was realised on the unpolished side by evaporating Au:Ge (88:12) alloy followed by 5 min annealing at 725 K under argon atmosphere. The Schottky contacts were made on the polished surface by evaporating palladium (Pd) of 7.85×10^{-3} cm^{-2} area and of thickness 200 nm. All evaporations were carried out under a vacuum of 1×10^{-6} mbar.

The fabricated SBDs were irradiated with 60 keV protons at different fluences 1×10^{14}, 1×10^{15} and 1×10^{16} cm^{-2}. The irradiations were carried out at room temperature and at a background pressure of the order of 8×10^{-7} mbar [6]. The current–voltage (*I–V*) and current–voltage–temperature (300–360 K) (*I–V–T*) characteristics of the SBDs were measured under dark conditions. Capacitance–voltage (*C–V*) measurements were carried out at room temperature using an automated system of 1 MHz Boonton 7200 capacitance meter.

3. Results and discussions

3.1. Current–voltage characteristics

The *I–V* curve has been characterized using the following:

$$J = J_s\left[\exp\left(\frac{qV}{nk_BT}\right) - 1\right], \tag{1}$$

where

$$J_s = A^{**}T^2 \exp\left(\frac{q\Phi_b}{k_BT}\right), \tag{2}$$

$$\Phi_b = V_T \ln\left(\frac{AA^{**}T^2}{J_s}\right), \tag{3}$$

where A^{**} is the effective Richardson's constant (A cm^{-2} K^{-2}); T is the absolute temperature (K); n is the ideality factor; k_B is Boltzmann's constant (J K^{-1}); Φ_b the barrier height (eV); J_s is the saturation current density (A cm^{-2}); V is the applied voltage, J the current density (A cm^{-2}) and V_T the thermal voltage.

There are several mechanisms which may account for the *I–V* and *C–V* characteristics after the irradiation. These include tunneling, carrier compensation and generation-recombination. Fig. 1 shows the *I–V* characteristics of the as-irradiated GaAs for different fluences of 1×10^{14}, 1×10^{15} and 1×10^{16} p cm^{-2}. The change in reverse leakage current (ΔI_R) increases as a function of fluence. For higher fluences the saturation current is high compared to CONTROL SBDs, which can probably be due to the irradiation induced defects at the interface, that induce tunneling through the barrier. Even if tunneling electrons are captured by defect levels in the damaged region, they may be thermally emitted from these

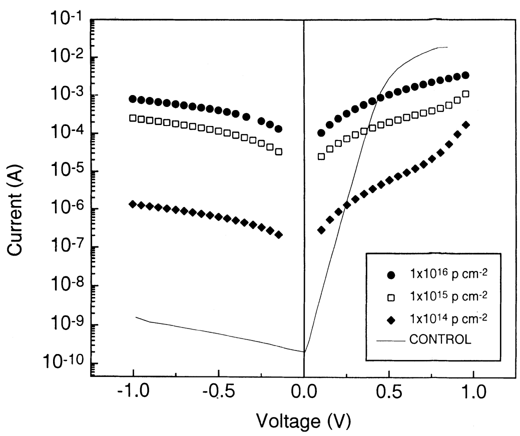

Fig. 1. *I–V* Characteristics of CONTROL and as-irradiated (1×10^{14}, 1×10^{15}, 1×10^{16} p cm^{-2}) SBDs.

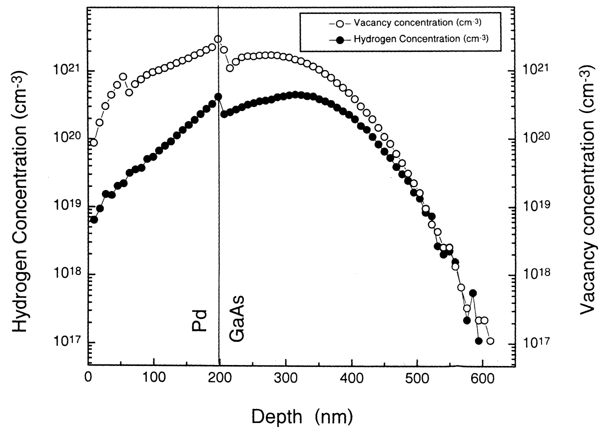

Fig. 2. Hydrogen and vacancy concentration vs. depth of 60 keV (fluence 1×10^{16} cm^{-2}) proton in GaAs.

levels to the conduction band. This mechanism enhances a charge flow in the reverse direction due to the high density of irradiation defects at the interface. For the present studies the proton energy has been chosen as 60 keV to create damage at the near interface of the SBDs. The hydrogen and vacancy concentration created by 60 keV proton for the fluence 1×10^{16} cm^{-2} as a function of depth obtained from TRIM95 are shown in Fig. 2.

Figs. 3 and 4 clearly show that ΔI_R increases and barrier height decreases as a function of incident particle fluence and for subsequent annealing ΔI_R decreases and the barrier height increases. This is due to the reduction of the irradiation induced defects upon annealing. Fig. 5 shows the I–V characteristics of CONTROL SBDs annealed at three different temperatures. Up to 473 K annealing, there is no change in the I–V characteristics. The ΔI_R value increases slightly for the diodes annealed at 573 K and the value further increases for 673 K annealing. This may be due to the formation of a thin heavily doped GaAs layer at the interface [7]. The reverse leakage current is less for the irradiated SBDs annealed at 673 K than the CONTROL SBDs for the same annealing temperature. This may be attributed to the irradiation induced defects that has not been annealed out completely, which gives rise to a comparatively high resistivity region below the junction.

For the irradiated diodes the activation energy and the Richardson's constant (A^{**}) values have

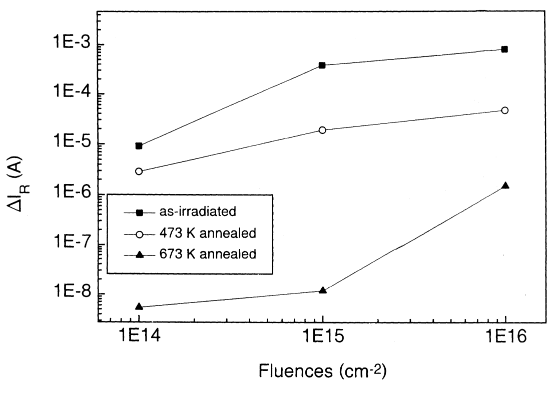

Fig. 3. Change in reverse leakage current vs. fluences at 0.9 V for as-irradiated and annealed (at 473 and 673 K) SBDs.

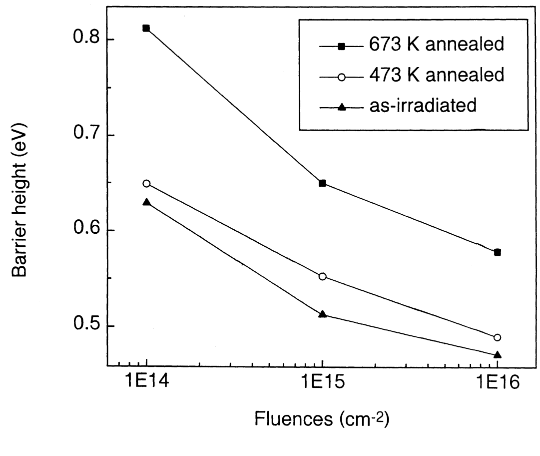

Fig. 4. Barrier height vs. fluences for as-irradiated and annealed SBDs.

Table 1
The effective barrier height (Φ_e), Richardson's constant (A^{**}), series resistance R_s and ideality factor values for the Pd/n-GaAs irradiated and annealed samples

Fluences	Samples	Φ_e (eV)	A^{**} (A cm^{-2} K^{-2})	R_s (Ω)	n
CONTROL		0.89	0.994	15	1.1
1×10^{14} p cm^{-2}	As-irradiated	0.47	0.99	150	1.4
	673 K Annealed	0.5		41.1	1.2
1×10^{15} p cm^{-2}	As-irradiated	0.39	0.99	150	6.8
	673 K Annealed	0.45		43	1.3
1×10^{16} p cm^{-2}	As-irradiated	0.35	0.99	–	–
	673 K Annealed	0.38			

been determined using $\ln(J_s/T^2)$ vs. $1000/T$ plot. The series resistance (R_s) and ideality factor values of the SBDs have also been evaluated from $\mathrm{d}V/\mathrm{d}I$ vs. $1/I$ plot. The evaluated values are given in Table 1. These plots are not linear as the metal–semiconductor interface is heavily damaged by protons which cause an increase in the R_s and reduction in the effective barrier height of the SBDs.

3.2. Capacitance–voltage measurements

The C–V curves were analyzed using the depletion capacitance equation

$$C = \frac{\varepsilon A}{W_d} = \sqrt{\frac{q\varepsilon N A^2}{2(V_{bi} - V - V_T)}},$$

where A is the area of the diode, N the free carrier concentration, V_T the thermal voltage ($=kT/q$), V the applied bias, W_d the depletion width, and V_{bi} the built-in voltage which is related to the barrier height Φ_b by the following:

$$\Phi_b = V_{bi} + V_T \ln\left(\frac{N_c}{N_d}\right),$$

N_c is the effective density of states at the conduction band (equal to 4.7×10^{17} cm^{-3} at 300 K for GaAs) and N_d is the donor concentration.

Before irradiation, the carrier concentration (4×10^{17} cm^{-3}) and the barrier height (0.89 eV) values have been evaluated using the C–V data. This barrier height value is in good agreement with those calculated from our I–V and I–V–T measurements.

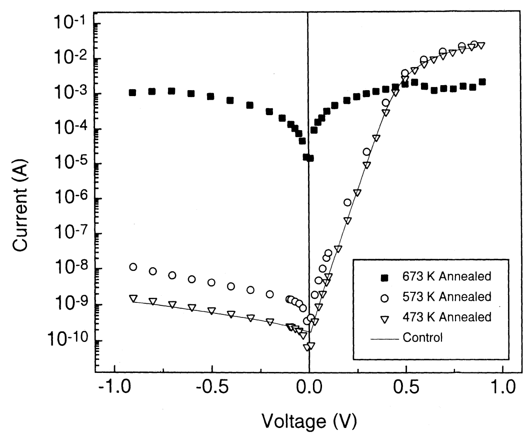

Fig. 5. I–V characteristics of CONTROL SBDs annealed at different temperatures.

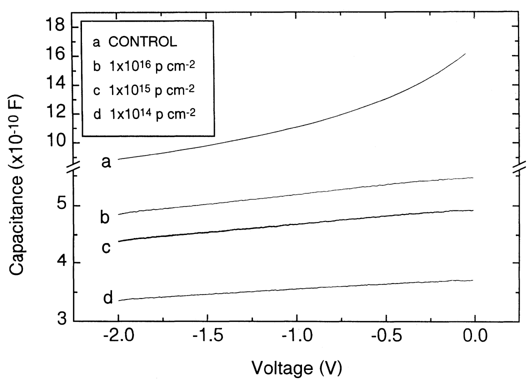

Fig. 6. C–V characteristics of CONTROL and as-irradiated SBDs.

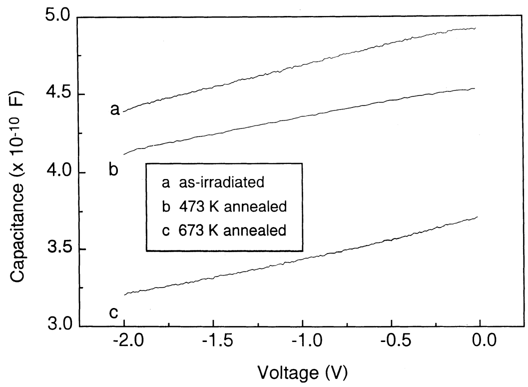

Fig. 7. *C–V* characteristics of as-irradiated and annealed SBDs for the fluence 1×10^{15} p cm^{-2}.

The capacitance values of the irradiated diodes were in general lower than that of the CONTROL diodes and showed very weak dependence on the applied voltage (Fig. 6). This is expected in view of the series resistance present in the circuit due to the passivation and damage layer in the GaAs below the junction. The observed rise in capacitance with increase in fluence (1×10^{15} and 1×10^{16} p cm^{-2}) may, on the other hand, be attributed to an increase in the depletion region permittivity [8]. It is observed that on annealing the irradiated SBDs at higher temperatures of 473 and 673 K, the capacitance further decreased compared to the as-irradiated diodes (Fig. 7, for the fluence 1×10^{15} p cm^{-2}). The same trend has been observed for the fluences of 1×10^{14} and 1×10^{16} p cm^{-2}.

4. Conclusions

The effect of interface defects on Pd/n-GaAs created by low-energy proton irradiation have been analyzed using *I–V* and *C–V* measurements. *I–V* measurements exhibit an increase in the change in reverse leakage current as a function of the incident particle fluence. It was found that for the annealed irradiated SBDs the diode characteristics improved, as compared to the as-irradiated SBDs. *C–V* measurements reveal that the defects introduced near the interface during proton irradiation could degrade the performance of the diodes. The capacitance decreases for the SBDs irradiated at a fluence of 1×10^{14} p cm^{-2} and for higher fluences the capacitance increases. It was found that as a function of annealing temperature the capacitance further reduces compared to the as-irradiated SBDs.

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