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Implications of electron beam irradiation on Al/n-Si Schottky junction properties

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ABSTRACT

The 7.5 MeV electron beam irradiation (EBI) effects on the Al/n-Si Schottky junction properties is studied in detail by analyzing I-V characteristics, power law characteristics, photoelectron spectra and energy band diagrams. The modifications in the junction parameters such as Schottky barrier height (Φ_B), ideality factor (n), and series resistance (R_S) at different irradiation doses are caused due to the formation of Al_2O_3-SiO_2 dielectric medium in the interface of Al and n-Si. As a result, Φ_B and band bending properties of the junction were modified. A linear correlation of Φ_B with EBI dose, interface trap states (m) and effective work functions (EWFs) suggests that the EBI technique is particularly advantageous for the miniature of devices which use band lineup as a key parameter in the device processing.

1. Introduction

The rectifying metal-semiconductor (MS) or Schottky junctions find number of applications in semiconductor device technology [1]. The precise relationship between the structure, chemical composition and the electrical properties at the Schottky junction is both of fundamental and technological interest. Beside interest on the bulk electronic properties, current advances in the capability of measuring precise surface and interface properties, allowed many experimental and theoretical studies on the Schottky junction [2,3]. However, the nature of Schottky interface or simply the Schottky barrier height (Φ_B) is still questionable. The detailed mechanisms involved in the interfacial region were proven to be difficult to identify due to irregularities in the arrangement of atoms lying in the interface region.

Obtaining the desirable MS junction properties or optimal Schottky barriers is crucial to the device optimization in the field of optoelectronics, microelectronics and energy conversion [1]. It is quite challenge to optimize both electronic and chemical properties for the simple metal contact to the semiconductor. Besides elemental composition, energy processing is a key macroscopic tool for achieving desirable interface properties. Such processes include furnace annealing, rapid thermal annealing with flash lamps, pulsed lasers, and electron beams [1]. The application of electron beam irradiation on the Schottky junctions could easily bring some interesting modifications in the junction properties. Since EBI affects the surface, interface and to some extent bulk electronic properties by inducing defect states [2]. Therefore, different electronic and chemical mechanisms can give rise to new junction properties that could dominate the barrier formation between metal and semiconductor.

In this paper, we report on the effect of EBI on the Al/n-Si Schottky junction properties. An in-depth analysis of current-voltage (I-V) characteristics and photoelectron spectroscopy studies is presented. The studies suggest that the modified interface chemistry could bring some interesting changes in the electrical properties of the junction. For example, the metal oxide semiconductor field-effect transistors (MOSFETs) and dynamic random access memories (DRAMs), where the band lineup at metal-insulator-semiconductor interfaces is an important design parameter [3].

2. Experimental method

The phosphorus doped Si (100) wafer having $N_D = 1.5 \times 10^{14}$ cm^{-3} was procured from Sigma Aldrich®, India. The diced ($10 \times 10 \times 0.5$ mm^3) and standard RCA cleaned n-Si wafers are deposited with Al contacts using thermal evaporation technique. The Al thickness and effective device area are kept at ~15 nm and 3.14×10^{-4} cm^{-2} respectively. The prepared Al/n-Si Schottky contacts are subjected to 7.5 MeV electron beam irradiation (EBI) using

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10 MeV linear accelerator (LINAC) present at Raja Ramanna Centre for Advanced Technology (RRCAT) India. The EBI parameters such as electron beam energy (7.5 MeV) and dose rate (6.5 kGy/s) were fixed throughout irradiation experiment. The EBI on prepared Al/n-Si Schottky contacts is performed at room temperature and at different irradiation doses (500, 1000, 1500 kGy). The other details of EBI parameters are detailed in our previous studies [2]. The I-V characterization was carried out using Keithly 2450 source meter under dark conditions. The copper pressure contacts were used as back ohmic contacts during measurements [2]. The x-ray photoelectron spectroscopy (XPS) investigations of both Si and Al/n-Si Schottky contacts were performed before and after EBI using Omicron energy analyzer (EA-125) with Al-kα (1486.7 eV) as a source of x-rays. The effective work function (EWF) measurements of Si and Al surface were carried out at 40 eV photon energy using synchrotron radiations (Indus-1 AIPES Beamline-2, RRCAT India).

3. Results and discussion

3.1. Analysis of I-V characteristics

Fig. 1 shows the I-V characteristics of Al/n-Si Schottky contacts at different irradiation doses. The variations in these characteristics at different EBI doses indicates the modified Schottky junction parameters such as Schottky barrier height (Φ_B) and ideality factor (n). These parameters are determined by applying thermionic-emission (TE) model. According to this model, the relationship between forward current (I) and applied voltage (V) [4,5].

$$I = I_s\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] \tag{1}$$

$$\text{where, } I_s = AA^{**}T^2\exp\left(-\frac{q\Phi_B}{kT}\right) \tag{2}$$

is the reverse saturation current, A is effective area of the diode, A^{**} is the Richardson constant (for n-Si, $A^{**} = 112\ \mathrm{A\cdot cm^{-2}K^{-2}}$ [4]), q is charge of the electron, Φ_B is Schottky barrier height, k is Boltzmann constant and T is absolute temperature. The parameter n in Eq. (1) is known as ideality factor, which accounts for the non-ideal behavior of Schottky diode [3,4].

For $V > 3kT/q$, the term -1 in Eq. (1) can be neglected. We obtain a straight line equation of the form

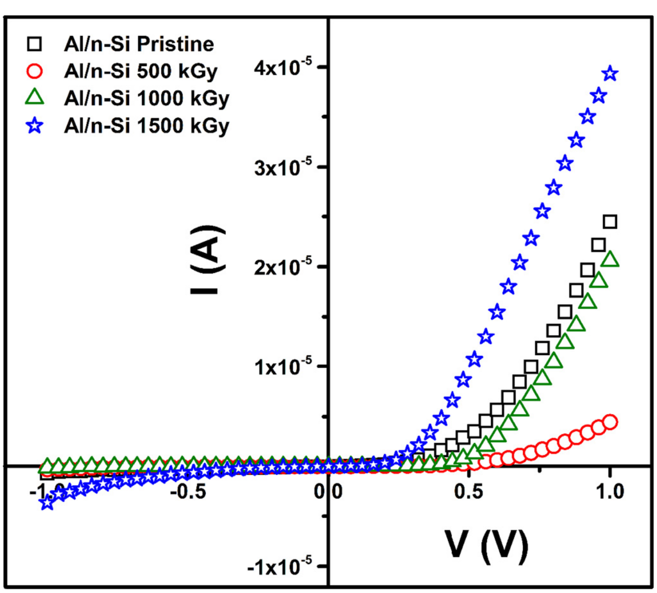

Fig. 1. I-V characteristics of Al/n-Si Schottky junctions irradiated at different doses.

Table 1
Schottky diode parameters of Al/n-Si Schottky contacts at different electron beam irradiation doses of 7.5 MeV electrons.

Diode	TE model		Cheung model		
	Φ_B (eV)	n	Φ_B (eV)	n	R_s (kΩ)
Al/n-Si Pristine	0.78	3.49	0.77	3.19	23.11
Al/n-Si 500 kGy	0.82	4.45	0.80	4.36	49.86
Al/n-Si 1000 kGy	0.84	3.20	0.86	2.65	11.85
Al/n-Si 1500 kGy	0.79	2.29	0.79	2.14	12.99

$$\ln I = \frac{qV}{nkT} + \ln I_S \tag{3}$$

The slope and intercept of the lnI vs. V plot gives the parameters n and Φ_B respectively. For all the Al/n-Si contacts, these parameters are extracted in the voltage range where the best line of fit (r = 0.99) was obtained in the forward lower bias voltage region.

Table 1 gives Φ_B and n values before and after EBI. The obtained values agree well with the values of the other four identically prepared and irradiated Schottky contacts. As noticed, the variations in these parameters indicates that the Al/n-Si Schottky junction is strongly affected due to the generation of EBI induced defect states and interface trap states. However, to account for the actual variation of n and Φ_B with EBI dose the effect of series resistance R_S on these parameters must be considered in the evaluation method. This can be done by applying Cheung model. According to this model, the TE model Eq. (1) for $V > 3kT/q$ takes the form [5].

$$I = I_s\left[\exp\left(\frac{q(V - IR_s)}{nkT}\right)\right] \tag{4}$$

Differentiation of Eq. (4) with respect to I gives,

$$\frac{dV}{d(\ln I)} = R_sI + \frac{nkT}{q} \tag{5}$$

The slope and intercept of the $\frac{dV}{d(\ln I)}$ vs I plot gives R_s and n respectively. On the other hand, Φ_B and R_s can be determined by plotting following relation:

$$H(I) = R_sI + n\Phi_B \tag{6}$$

where,

$$H(I) = V - \frac{nkT}{q}\ln\left(\frac{I}{AA^{**}T^2}\right) \tag{7}$$

In determining H (I) and Φ_B from above equations, it is required to consider the n value obtained from Eq. (5) plot. Also, for the better accuracy, the downward curvature region of the linear I-V characteristics (Fig. 1) must be selected [2,6].

As noticed from Table 1, the variations in Φ_B and n values between TE and Cheung model is attributed to the effect of R_s which was not considered in the TE model. Primarily, R_s is originated from the presence of a thin oxide layer between Al and n-Si interface as well as contribution from the bulk n-Si. Due to high value of R_s and $n > 1$, the Al/n-Si contacts are exhibiting non-ideal I-V characteristics. However, variation in their values after EBI is a consequence of modified nature of interface properties between Al and n-Si.

3.2. Power law characteristics

It is well-known that, the ideality factor (n) is simply the manifestation of the homogeneity of interface. For an ideal homogeneous interface n must be unity. However, most practical Schottky contacts exhibit greater than unity ideality factors. This is due to inhomogeneous nature of the interface or barrier Φ_B [7]. In the present case, $n > 1$