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OPTICAL RESPONSE STUDY OF THE Al/a-SiC:H SCHOTTKY DIODE FOR DIFFERENT SUBSTRATE TEMPERATURES OF THE r.f. SPUTTERED a-SiC:H THIN FILM

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In the present work, Schottky diodes of Al/a-SiC:H included in the structure Al/a-SiC:H/c-Si(n)/Al were fabricated and their optical response was studied in the wavelength region from 350 nm up to 1000 nm, for different substrate temperatures, T_s (from 30 °C up to 290 °C) of the r.f. sputtered a-SiC:H thin film. The spectral response of these structures exhibits two maximum values of quantum efficiency. The first maximum is presented at wavelength $\lambda \cong 525$ nm and the other at $\lambda = 850$ nm, which are attributed to the Al/a-SiC:H Schottky junction and the a-SiC:H/c-Si(n) isotype heterojunction, respectively. The position of the first maximum owing to the Al/a-SiC:H junction as well as the values of quantum efficiency, for the range of wavelengths from 350 nm up to 700 nm, depends on the substrate temperature, T_s, of the a-SiC:H thin film. In the case that T_s is 120 °C, the spectral response of the Al/a-SiC:H/c-Si(n)/Al structure for a reverse bias voltage $V = -2$ V exhibits high values of quantum efficiency (up to 40%) with slight variation in the range of wavelength from 475 nm up to 925 nm, making this structure interesting as a wide band optical sensor device. Finally, the minority carrier (holes) diffusion length of a-SiC:H for $T_s = 120$ °C was calculated and it was found to be $\cong 2.200$ Å.

Keywords: Schottky diode; Optical sensor; Heterojunction; Diffusion length

1 INTRODUCTION

A-SiC:H is a very promising material in many optoelectronic applications such as solar cell [1], color detector [2], light emitting diode and phototransistor [3]. The properties of the above devices can be affected by changing the deposition parameters of the a-SiC:H thin films, which have crucial effects on the optical and optoelectronic properties of a-SiC:H films. Schottky diodes on a-SiC:H are also very important in their own right and can be used for the understanding and characterization of a-SiC:H and its devices. Despite the importance of a-SiC:H Schottky diodes, there is a dearth of relevant publications [4, 5]. Consequently, much work is needed in this area in order to understand, and then to improve the optoelectronic properties of Metal/a-SiC:H diodes.

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The present work is a contribution to this particular direction. More specifically, the optical response of the Al/a-SiC:H Schottky junction included in the structure Al/a-SiC:H/c-Si(n)/Al is studied, for different substrate temperatures of the r.f. sputtered a-SiC:H thin film. The experimental results show that the values of quantum efficiency as well as the position of the maximum value owing to the Al/a-SiC:H Schottky junction depend on T_s. For $T_s = 120\,^{\circ}\mathrm{C}$ the overall spectral response of the above structure (Al/a-SiC:H/c-Si(n)/Al) presents high values of quantum efficiency with slight variation in the range of wavelengths from 475 nm up to 925 nm, making it interesting as a wide-band optical sensor device.

2 FABRICATION OF THE Al/a-SiC:H SCHOTTKY DIODE

A-SiC:H thin films of thickness 5000 Å were deposited by r.f. sputtering on n-type c-Si ($\rho = 5$–$10\,\Omega$cm) substrates, with ohmic contacts (Al) on their back sides. The target used was poly-SiC of constant composition (C 66 wt.% and Si 34 wt.%) and 99.8% purity. The r.f. power was 250 W and the target to substrate distance was 5.5 cm. The substrate temperature was varied from 30 °C up to 290 °C and the sputtering chamber evacuated to a pressure lower than 5×10^{-7} Torr, before the introduction of argon. During deposition, the flow rate of argon and hydrogen was 20 sccm, and the pressure in the sputtering chamber was 5×10^{-3} Torr. After the deposition of a-SiC:H thin films, the samples were placed in a

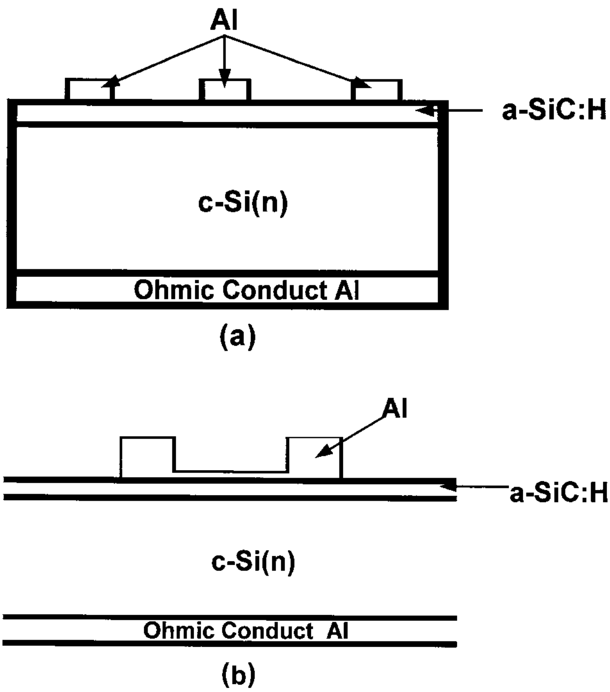

FIGURE 1 (a) Typical structure of the Al/a-SiC:H Schottky diode. (b) Typical structure used for the measurement of the spectral response of the Al/a-SiC:H Schottky diode.

high vacuum evaporator, where aluminum dots (1 mm in diameter) were deposited on the amorphous thin films. Figure 1(a) shows the typical structure of the Al/a-SiC:H Schottky diode used in the present work.

In order to study the spectral response of the Al/a-SiC:H Schottky diode, the Al electrode on the amorphous thin film had the shape shown in Figure 1(b). The metal film in the center of the circular disc was very thin (<80 Å), in order to be transparent to the incident light, whereas at its circumference it was much thicker (about 5000 Å) for the electrical connection. To get this form of Al, the as-deposited Al dots were chemically etched using the photolithography process [6].

3 EXPERIMENTAL RESULTS

Previous works [7–9] have shown that the r.f. sputtered a-SiC:H thin film exhibits n-type conductivity and the junction Al/a-SiC:H behaves as a Schottky one, with very good rectification properties. Also, these works have shown that the optical band gap, E_g, of the a-SiC:H increases from 2.05 eV up to 2.30 eV with the respective increase of substrate temperature, T_s, from 30 °C up to 290 °C, and the photosensitivity presents the optimum value at $T_s = 120\,°C$ [8], as well. Figure 2 presents the energy band diagram of the Al/a-SiC:H/c-Si(n)/Al structure under thermal equilibrium conditions for the case that the a-SiC:H deposited at 120 °C. The above energy band diagram was derived using Anderson's model [10]. The subscripts 1 and 2 refer to a-SiC:H and c-Si(n), respectively, so that E_{C1}, E_{C2} are the edges of conduction bands, E_{V1}, E_{V2} the edges of valence bands, δ_1, δ_2 the distances between the Fermi level and the corresponding conduction band edges, E_{g1}, E_{g2} the energy bandgaps, ΔE_C, ΔE_V the discontinuities of the conduction and valence bands, respectively,

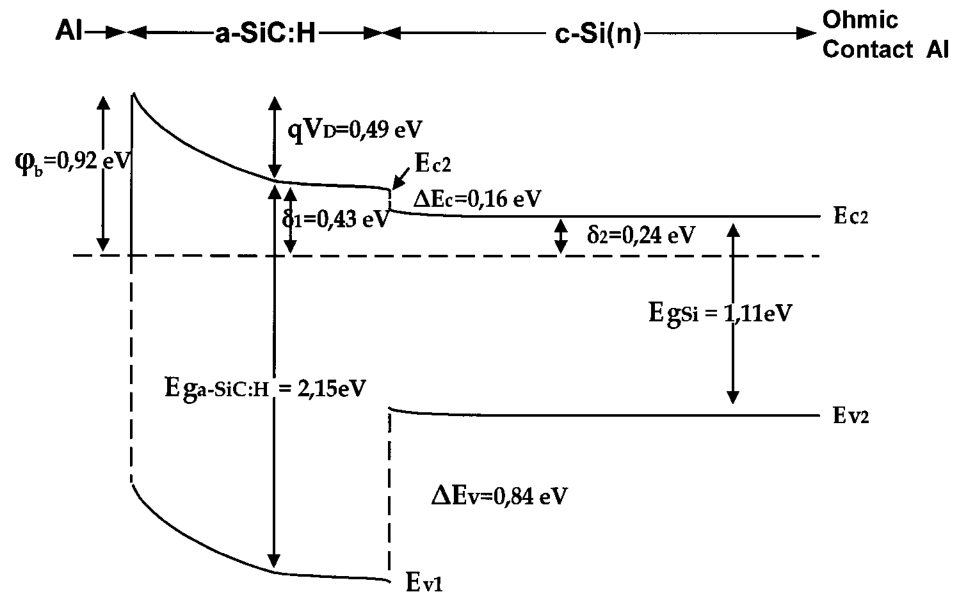

FIGURE 2 Energy band diagram of the Al/a-SiC:H/c-S(n)/Al structure under quasi equilibrium.

E_F the Fermi level under thermal equilibrium conditions, φ_b the potentials barrier of the Schottky junction, V_D, V_b the total diffusion potential of the Al/a-SiC:H junction and the a-SiC:H/c-Si(n) junction, respectively, and V_{b1}, V_{b2} the partial diffusion potentials of the a-SiC:H/c-Si(n) junction. Take into account that $\varphi_b = 0.92$ eV [9], $V_D = 0.49$ eV [7, 9], $\delta_1 = 0.43$ eV [7], $\delta_2 = 0.24$ eV (extracted from the resistivity value of Si), and the well known values of Al work function ($W_{b\mathrm{Al}} = 4.28$ eV [6]) and the electron affinity of c-Si ($X_{\mathrm{Si}} = 4.01$ eV [11]), the value of V_b was calculated to be $V_b = 0.03$ eV, since $V_b = W_{b\mathrm{Al}} - (X_{\mathrm{Si}} + \delta_2)$.

According to the following relations [11]:

$$\Delta E_C = \delta_1 - \delta_2 + V_{b1} - V_{b2} \tag{1}$$

$$\Delta E_V = E_{g1} - \delta_1 - (E_{g2} - \delta_2) + V_{b1} - V_{b2} \tag{2}$$

and the reasonable assumption that $V_b \cong V_{b2} \cong 0.03$ eV, provided that the a-SiC:H/c-Si(n) was determined to be an almost one-sided junction [8], the quantities ΔE_C and ΔE_V were calculated, and found to be $\Delta E_C = 0.16$ eV and $\Delta E_V = 0.84$ eV.

Figure 3 shows the experimental results of the spectral response of the Al/a-SiC:H Schottky junction included in the structure Al/a-SiC:H/c-Si(n)/Al for $T_s = 120\,^\circ$C with the respect $E_{g\,\text{a-SiC:H}} = 2.15$ eV, and for two different reverse bias voltages, $V = -0.5$ V and $V = -2$ V. As it is clear from this figure for a given reverse bias voltage the measured quantum efficiency, η_{measured}, exhibits two maximum values, one at wavelength $\lambda \cong 525$ nm and the other at $\lambda = 850$ nm. Both of these maximum values can be attributed to the existence of the Al/a-SiC:H Schottky junction and the a-SiC:H/c-Si(n) isotype

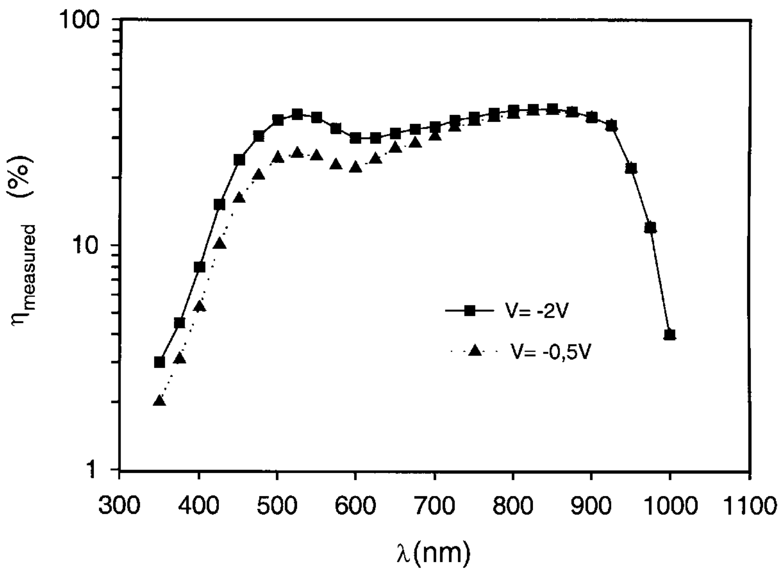

FIGURE 3 Measured quantum efficiency, η_{measured}, of the Al/a-SiC:H Schottky diode included in the Al/a-SiC:H/c-S(n)/Al structure as a function of the wavelength, λ, for a reverse bias voltage $V = -2$ V (■) and $V = -0.5$ V (▲), and for substrate temperature $T_s = 120\,^\circ$C.

heterojunction, respectively, since the positions of the two maximum values are slightly smaller to the respected E_g of a-SiC:H and c-Si(n), respectively [12]. Also, from the same Figure 3 it is obvious that the first maximum at wavelength $\lambda \cong 525$ nm depends on reverse bias voltage, V, in contradiction with the second one. This behavior can be explained by taking into account that the partial applied voltage, V_1, on the junction Al/a-SiC:H is much higher than the other one, V_2, of the junction a-SiC:H/c-Si(n), since ($V_D/V_b > 10$) [10], as it was calculated above. In accordance to the above fact, the increase of the reverse bias voltage, from $V = -0.5$ V to $V = -2$ V, causes an increase of the depletion region width of the Al/a-SiC:H junction, leading to higher values of the quantum efficiency of the first maximum only, whereas the values of the second maximum remain almost constant. The possibility that interface or subgab states contribute to the second maximum is not acceptable, since excitations from these states present very low values of the absorption coefficient, $\alpha(<10^3\,\mathrm{cm}^{-3})$, and their total contribution to the quantum efficiency is few percent [13, 14]. For higher values of reverse bias voltage the quantum efficiency remains almost constant. This means that the volume effect have been saturated or the lack of additional available photogenerated carriers in a-SiC:H. It must be pointed out that the electrical study of the Al/a-SiC:H Schottky diode included in the Al/a-SiC:H/c-Si(n)/Al structure [9] did not reveal the existence of another barrier, due to the a-SiC:H/c-Si(n) isotype heterojunction, since this barrier presents lower height in comparison with the Schottky one, as it was found in the present work.

Consequently, illuminating the structure Al/a-SiC:H/c-Si(n)/Al from the side of the Al/a-SiC:H junction, the high energy photons are absorbed near the surface of the a-SiC:H, resulting in the generation of electron–hole pairs which cross the depletion region (electron and holes moving in opposite directions) of the Schottky junction and they are collected. As the wavelength, λ, increases, the a-SiC:H gradually becomes more and more transparent, and the main region, where absorption of photons takes place, is shifted towards the a-SiC:H/c-S(n) junction, where the photogenerated carriers are collected. The measured quantum efficiency, thus, η_{measured}, is the total result of the spectral response of both junctions, Al/a-SiC:H, η_1, and a-SiC:H/c-S(n), η_2:

$$\eta_{\mathrm{measured}} = \eta_1 + \eta_2 \tag{3}$$

Taking into account that the photosensitivity of a-SiC:H and c-Si have different spectra [12,15], as well as the a-SiC:H/c-Si(n) junction was determined to be an almost one-sided junction [8], the measured quantum efficiency in the range of wavelengths from 350 nm up to 550 nm is approximately equal to η_1, ($\eta_{\mathrm{measured}} \cong \eta_1$). On the other hand the total quantum efficiency in the range of wavelengths from 700 nm up to 1000 nm is approximately equal to η_2 ($\eta_{\mathrm{measured}} \cong \eta_2$). The positions of two maximum values of the measured quantum efficiency at 525 nm and 850 nm are slightly smaller to the respected E_g of a-SiC:H and c-Si(n), respectively, [12]. These are given, qualitatively, in Figure 4.

The experimental results of Figure 3 show that the overall optical response of the Al/a-SiC:H/c-S(n)/Al structure for reverse bias voltage $V = -2$ V and $T_s = 120\,^{\circ}$C exhibits high values of the measured quantum efficiency ($\cong 40\%$) with slight variation in the wavelength region from 475 nm up to 925 nm. This behavior makes this structure interesting as a wide-band optical sensor device. Also, from the experimental results of the same figure for

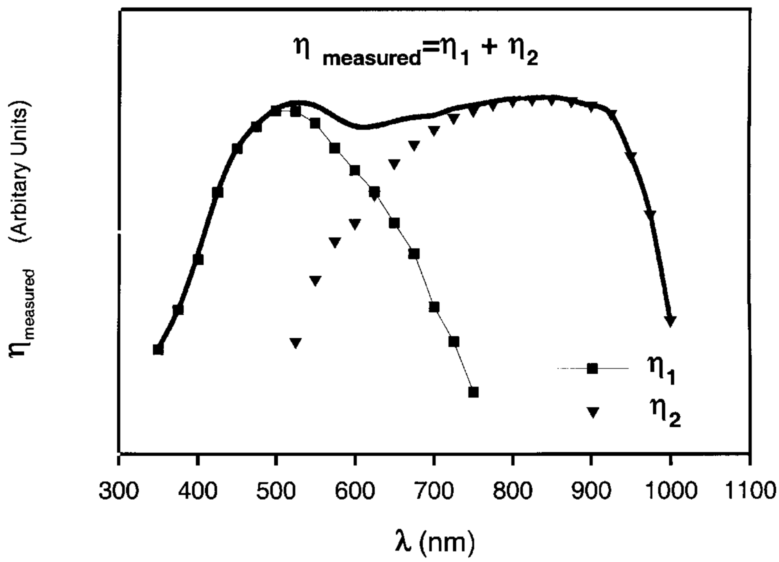

FIGURE 4 Qualitative spectral response of the Al/a-SiC:H Schottky diode included in the structure Al/a-SiC:H/c-S(n)/Al. The solid line represents the measured quantum efficiency η_{measured}.

the range of λ up to 525 nm, where the spectral response is due to the Al/a-SiC:H junction only, and the expression [12]:

$$\eta_{\text{measured}} = (1 - R)\left(1 - \frac{\exp(-\alpha w)}{1 + \alpha L_p}\right) \tag{4}$$

where w is the thickness of the depletion region width in a-SiC:H of the Al/a-SiC:H junction, R is the incident light reflectance of the Al surface, and α is the a-SiC:H absorption coefficient, the value of diffusion length of a-SiC:H holes, L_p, may be calculated. It was found to be $L_p \cong 2.200$ Å, which is in good agreement with the results from other work [16] for a-SiC:H thin films prepared by glow discharge technique. For the above calculations the values of R and α were taken from other previous works [17, 18], and equal to 52% and $3.5 \times 10^4\,\text{cm}^{-1}$, respectively. Also, the thickness of w was determined to be about 2.500 Å, by using the estimated value of the effective density of localized states in a-SiC:H ($\cong 5 \times 10^{16}\,\text{cm}^{-1}$) [8].

Figure 5 shows the spectral response of the Al/a-SiC:H Schottky diode included in the Al/a-SiC:H/c-Si(n)/Al structure for a reverse bias voltage $V = -2$ V and for three different T_s, *i.e.* 30 °C, 120 °C, 290 °C with $E_{g\,\text{a-SiCi:H}}$ 2.05 eV, 2.15 and 2.30 eV, respectively. As it is clear from this figure the spectral response of these structures for $T_s = 30$ °C and $T_s = 290$ °C presents lower values of quantum efficiency in comparison with that of $T_s = 120$ °C, in the range of wavelengths from 350 nm up to 700 nm. This result can be attributed to the fact that the a-SiC:H thin film deposited at $T_s = 120$ °C presents the optimum optoelectronic properties [8]. Also, from the same figure it is obvious that the position of the first maximum, owing to the Al/a-SiC:H Schottky junction, depends on the value of $E_{g\,\text{a-SiC:H}}$. More speci-

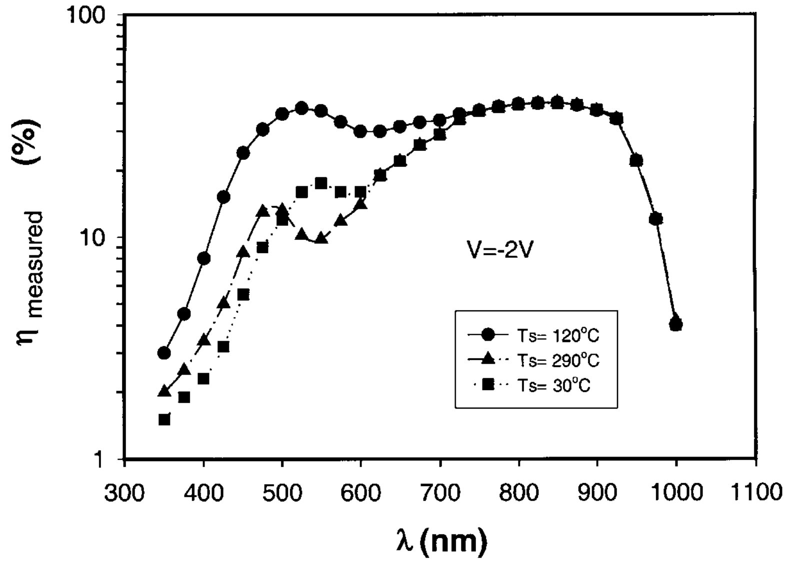

FIGURE 5 Measured quantum efficiency, η_{measured}, of the Al/a-SiC:H Schottky junction included in the Al/a-SiC:H/c-S(n)/Al structure, as a function of the wavelength, λ, for a reverse bias voltage $V = -2$ V and for three different substrate temperatures $T_s = 30\,°C$ (■), $T_s = 120\,°C$ (●) and $T_s = 290\,°C$(▲).

fically, as the $E_{g\,\text{a-SiC:H}}$ increases the wavelength of the maximum shifts towards the lower wavelength, according to the relation:

$$\lambda(\mu\text{m}) = \left(\frac{1.24}{E_g}\right) \tag{5}$$

This behavior, in conjunction with the fact that the optical band gap of a-SiC:H can be controlled, is very interesting for preparing wide band optical sensor devices, with high photosensitivity in the blue region of the spectra, by using a-SiC:H thin films of different E_g, in multi-layer heterojunction structures. Additionally, the values of quantum efficiency could be improved by using a suitable anti-reflect coating on the top electrode, since Al presents high values of reflectance in the visible region of wavelengths.

4 CONCLUSIONS

The main conclusions of this work are the following:

1. The spectral response of the Al/a-SiC:H/c-Si(n)/Al structure exhibits two maximum values of quantum efficiency. The first maximum is presented at $\lambda \cong 525$ nm and the other at $\lambda = 850$ nm, which are attributed to the Al/a-SiC:H Schottky junction and the a-SiC:H/c-Si(n) isotype heterojunction, respectively. The position of the first maximum, owing to the Al/a-SiC:H Schottky junction, as well as the values of quantum efficiency, for the range of wavelengths from 350 nm up to 700 nm, were found to depend on the substrate temperature of the r.f. sputtered a-SiC:H thin film.

2. The overall spectral response of the Al/a-SiC:H/c-Si(n)/Al structure for substrate temperature of the a-SiC:H thin film $T_s = 120\,^\circ\mathrm{C}$ and a reverse bias voltage $V = -2\,\mathrm{V}$, exhibits high values of quantum efficiency in the range of wavelengths from 475 nm up to 925 nm, making this structure interesting as a wide-band optical sensor device.
3. The minority carrier (holes) diffusion length of a-SiC:H for $T_s = 120\,^\circ\mathrm{C}$ was calculated and it was found to be $\cong 2.200\,\text{Å}$.

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