Modification of interface states and series resistance properties of Al/p-type Si Schottky diode with HF chemical treatment

A. A. AL-GHAMDI[a], OMAR A. AL-HARTOMY[a,b], M. CAVAS[c], FARID EL-TANTAWY[d], F. YAKUPHANOGLU[e]
[a]*Department of Physics, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia*
[b]*Department of Physics, Faculty of Science, Tabuk University, Tabuk 71491, Saudia Arabia*
[c]*Maden Higher Vocational School, Firat University, Elazig, Turkey*
[d]*Department of Physics, Faculty of Science, Suez Canal University, Ismailia, Egypt*
[e]*Department of Physics, Faculty of Science, Firat University, Elazig 23169, Turkey*

The Al/p-type Si Schottky diode was fabricated with chemical treatment to modify its interface states and series resistance properties. The barrier height, ideality factor and series resistance parameters of the diode were determined by performing Cheung plots. The barrier height, ideality factor and series resistance values of the diode were found to be 0.67 eV, 1.65 and 4.93 kΩ, respectively. The passivaiton of the surface of the silicon increases the value of Schottky barrier height. The barrier height of the studied diode is higher than that of conventional Al/p-Si diodes. The ideality factor higher unity may be attributed to the chemical oxide layer grown on the semiconductor. The density of the interface states without series resistance is higher than that of with series resistance. It is evaluated that the series resistance value should be taken into account in determining the interface state density distribution. The density of interface states of the diode studied is of the order of $1.93\mathrm{x}10^{13}$ $\mathrm{eV}^{-1}\mathrm{cm}^{-2}$. The obtained results indicate that HF chemical treatment modifies the interface states and series resistance properties of Al/p-Si Schottky diode.

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1. Introduction

The metal–semiconductor (M–S) contact in the semiconductor device technology is still investigated and has attracted much attention during recent years [1-3]. Interfaces between metals and semiconductor modify the electronic parameters of the Schottky diodes and the quality of MS contacts depends on the preparation conditions. Furthermore, the reliability and stability of these devices are related to their interface conditions. The existence of an insulator layer between metal and semiconductor influence the interface states and can modify electrical properties of metal-semiconductor structures. This layer plays an important role in the determination of Schottky barrier height and interface states. The effect of the interfacial layer properties such as interfacial layer thickness and the interface states have drawn considerable interest during recent years [4-11]. The physical properties of Schottky diodes strongly depend on preparation conditions of surface and formation of interfacial layer. Their electrical characteristics have been extensively studied for decades [9-26].

In this study, the p-Si wafer was exposed to HF treatment at room temperature in order to form an interfacial insulator layer on the upper surface of the Si wafer after ohmic contact.

The main aim of this process is to modify the interface state density and modify the main electronic parameters of Al/p-Si Schottky diode.

2. Experimental

p-Si was used as substrate. In order to remove native oxide on surface on p-Si, the substrate was etched by HF and then was rinsed in deionised water using an ultrasonic bath for 10-15 min and finally was chemically cleaned according to method based on successive baths of methanol and acetone. After surface cleaning, Al metal with high purity (99.999%) was thermally evaporated on the substrate at pressure of $3.3\ 10^{-6}$ mbar in vacuum pump system. Al/p-Si structure was sintered at 450 ^{o}C for 15 min to obtain ohmic contact. Before Schottky metallization, HF chemical treatment was used and the front surface of the Si wafer was exposed to HF solution. After HF chemical treatment, Al contact was formed by thermal evaporation. The current–voltage (I-V) characteristic of the Al/p-Si diode was performed with 2400 KEITHLEY sourcemeter and GPIB data transfer card for current-voltage measurements.

3. Results and discussion

3.1. Current-voltage characteristics of Al/p-Si diode

Fig. 1 shows the current-voltage characteristic of the Al/p-Si diode. The diode exhibits an excellent rectification. The forward current-voltage characteristics of the Schottky barrier diode having interfacial layer can be expressed by [1,2]

$$I = I_o \, exp\left(\frac{q(V - IR_S)}{nkT}\right)\left[1 - exp\left(-\frac{q(V - IR_S)}{kT}\right)\right] \tag{1}$$

where n is the ideality factor, T is the temperature and I_o is the reverse saturation current and ϕ_B is the barrier height given by

$$q\phi_B = kT \, ln\left(\frac{AA^* T^2}{I_o}\right) \tag{2}$$

where I_o is the saturation current, A is the contact area, A* is the Richardson constant (112 $A.cm^{-2}.K^{-2}$ for n-type Si) [1].

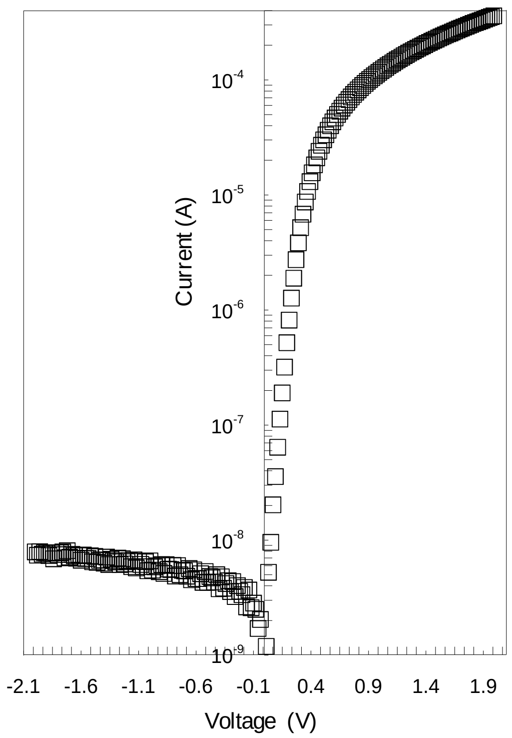

Fig. 1. Forward and reserve bias characteristics of Al/p-Si diode.

The ideality factor and barrier height values were determined from the slope and intercept of forward bias region of Fig.1 and HF treatment yields the barrier height of 0.67 eV and ideality factor of 1.43. The obtained n value is attributed to the presence of a thin chemical oxide layer on the silicon surface. The obtained ideality factor suggests a charge transport mechanism between thermionic emission and recombination current. The defects at Si/SiO_2 interface generate a recombination current which contributes to the Schottky contact current [27]. The ideality factor value of the studied diode is higher than that of A/p-Si diodes [28], whereas it is lower than those of the diodes [29-31]. Furthermore, the barrier height of the studied diode is higher than that of Al/p-Si diodes [29-31]. The Schottky barrier height on p-type Si is in the range of 0.4-0.7 eV independent of the metallization [32-35]. The passivaiton of the surface of the silicon increases the value of Schottky barrier height. The chemical treatment modifies the Schottky diode parameters of Al/p-Si Schottky diode. The ideality factor higher unity may be attributed to the chemical oxide layer grown on the semiconductor, suggesting that the potential barriers at real metal-semiconductor interfaces depend much more on the applied voltage than predicted ideal contacts [36]. Furthermore, the value of n higher than unity arises from due to several effects, for example, thermoionic filed emission, interface states at thin insulator layer between metal and semiconductor, generation-recombination, interface impurities, tunnelling, image force lowering of Schottky barrier in the high electric field at metal-semiconductor interface [37-38]. At higher voltages, the I-V characteristic of the diode deviates from linearity due to the existence of interfacial layer and series resistance effect. In such as case, in order to determine the diode parameters, we used the Cheung's method and Cheung's functions can be expressed as [39],

$$\frac{dV}{d\ln(I)} = n\frac{kT}{q} + IR_S \tag{3}$$

$$H(I) = V - n\frac{kT}{q}\ln\left(\frac{I_o}{AA^* T^2}\right) \tag{4}$$

and

$$H(I) = IR_S + n\phi_B \tag{5}$$

where R_s is the series resistance and ϕ_B is the barrier height. Fig. 2 shows the plots of dV/dlnI vs. I and H(I) vs. I.

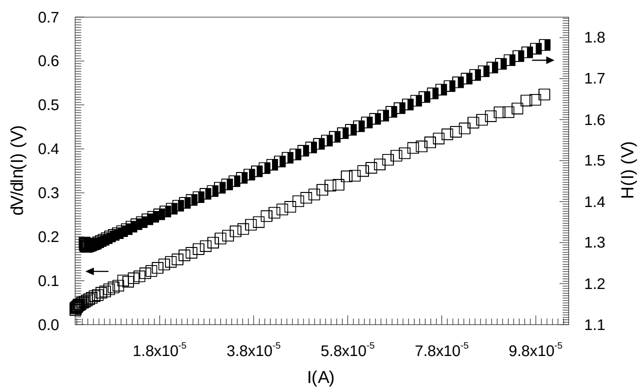

Fig. 2. Plots of dV/dln(I) vs I and H(I) vs I of Al/p-Si diode.

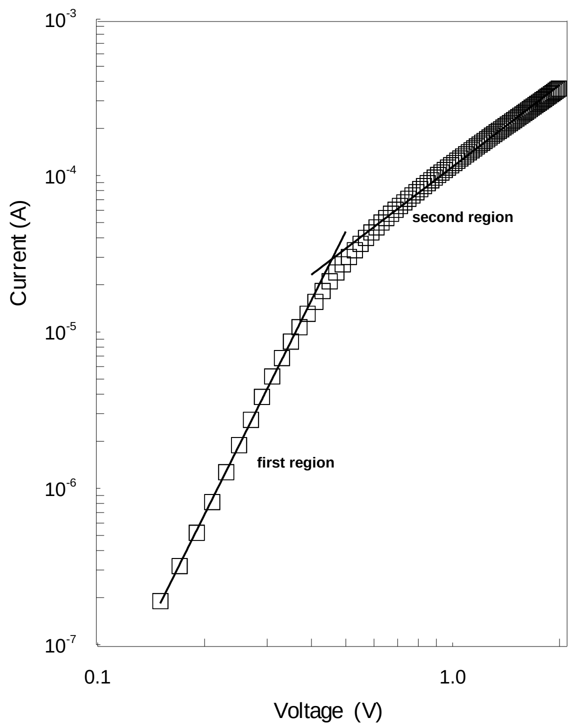

Fig. 3. Plot of I-V of Al/p-Si diode in semilogarithmic scale.

The plots give a straight line in series resistance region. The R_s and n values were calculated from the slope and intercept of dV/dlnI vs. I plot. The obtained values are R_s=4.91 kΩ and n=1.65. The obtained diode parameters suggest that current-voltage characteristics of the diode are far from thermoionic emission model. The R_s obtained from H(I)-I plot is 4.95 kΩ. The average value of series resistance of the diode was found to be 4.93 kΩ. The series resistance of the studied diode is higher than that of Al/p-Si diodes [29-31]. This suggests that the chemical oxide layer increases the series resistance of the Al/p-Si. At higher voltages, I-V characteristic of Al/p-Si diode is affected due to series resistance. In order to analyze the higher voltage effects, the I-V characteristic of the diode was plotted in form of logarithmic (Fig. 3). This plot indicates two regions having different slopes. The first region indicates a super quadratic behaviour with slope of 4.55. In region II, the increase rate of current with voltage decreases, suggesting that most of traps are filled and contribution of free carrier to electric filed becomes appreciable [40]. The second region suggests a trap controlled space charge limited and the space charge limited current is expressed by the well-known relation,

$$I = \frac{9}{8}\varepsilon_o \varepsilon_s \mu_p \frac{A}{d^3} V^2 \tag{6}$$

where ε_o is the dielectric permittivity of vacuum, ε_s is the dielectric constant of the semiconductor, μ_p is the electron mobility and d is the thickness.

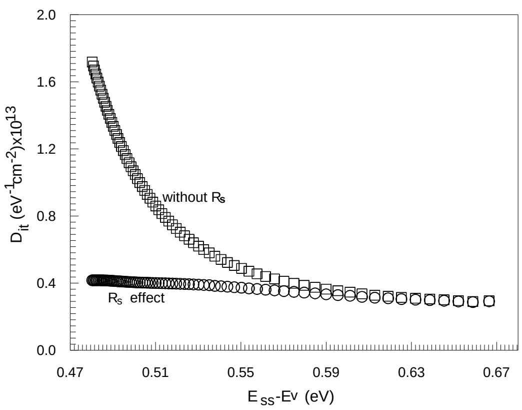

Fig. 4. The variation of D_{it} values with E_c-E_{ss} of Al/p-Si MIS diode.

The interface state density D_{it} for surface treatment can be determined using the following equation proposed by Cowley and Sze [41]

$$n = \frac{\varepsilon_i}{\varepsilon_i + q^2 \delta D_{it}} \tag{7}$$

where D_{it} is the density of the interface states, ε_i is the dielectric constant of the interfacial layer, and δ is the thickness of interfacial layer. The 1.65 ideality factor of the diode gives a interfacial layer of 27.36 Å. This thick interfacial insulator layer suggests that the D_{it} values are at equilibrium with the semiconductor and they cannot interact with the metal [1,2,41]. Furthermore, in p-type semiconductors, the energy of the interface states can be determined as [42],

$$E_{SS} - E_V = q(\phi_e - V) \tag{8}$$

where E_{ss} is the energy corresponding to the bottom of the conduction band at the surface of the semiconductor and ϕ_e is the effective barrier height depends on applied voltage due to an interfacial layer given by

$$\phi_e = \phi_B + \left(1 - \frac{1}{n}\right)(V - IR_s) \tag{9}$$

where n is dependent on voltage applied. The D_{it} values were obtained via the Eq. 7. The D_{it} dependence on E_{SS}-E_V is shown in Fig. 4. The density of the interface states without series resistance is higher than that of with series resistance. This suggests that a great of the interface states is passivated. Thus, it is evaluated that the series resistance value should be taken into account in determining the interface state density distribution. The density of interface states of the diode studied is of the order of 1.93×10^{13} eV^{-1} cm^{-2}. This value is in agreement with similar results reported in the literature [24,43].

The density of the interface states of the studied diode is lower than that of six Al/p-Si Schottky diodes with a native interfacial insulator layer [31]. This suggests that the interface quality of the silicon/ chemical oxide is better than that of the silicon/native oxide interface. The density of the interface states of the diode studied results from low density of dangling states. Experimental results show that the interface states at a native insulator layer between metal and semiconductor play an important role in the value of the barrier height, ideality factor, series resistance and the other main electrical parameters of Schottky diodes.

4. Conclusions

The interface state density and series resistance properties of Al/p-Si Schottky diode were investigated by current-voltage method. The barrier height, ideality factor and series resistance of the diode were determined to be 0.67 eV, 1.65 and 4.93 kΩ, respectively. The density of interface states of the diode studied is of the order of 1.93×10^{13} $eV^{-1}cm^{-2}$. The HF chemical treatment modifies the interface states and series resistance properties of Al/p-Si Schottky diode.

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*Corresponding author: fyhanoglu@firat.edu.tr