Time Dependence of Current–Voltage Characteristics of Pb/p-Si Schottky Diode under Hydrostatic Pressure

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The effect of time on the characteristic parameters of Pb/p-Si Schottky diodes has been presented as a function of hydrostatic pressure. Current–voltage curves of the Pb/p-Si Schottky diodes have been measured at immediate, 15, 30, 60, and 120 min intervals under 1, 2, and 4 kbar hydrostatic pressure. It has been found that the values of the ideality factor have been approximately unchanged with increasing time. On the other hand, the barrier height of the Pb/p-Si structure slowly increase with increasing time, while these parameters also change with hydrostatic pressure. The diode shows nonideal current-voltage behaviour with an ideality factor greater than unity that can be ascribed to the interfacial layer and the interface states. In addition, the Schottky barrier height increases with a linear pressure coefficient of 92 meV/kbar, which is higher than the pressure coefficient of the silicon fundamental band gap.

Key words: Schottky Barrier Diode; Barrier Height; Fermi Level Pinning; Metal Induced Gap States (MIGS) Model; Pressure Coefficient.

1. Introduction

The investigation of rectifying metal–semiconductor contacts (Schottky diodes) is of current interest for most elemental and compound semiconductors. Because of their technological importance, the properties of these contacts have been studied using a variety of techniques involving the capture or the emission of charge carriers, such as current-voltage ($I-V$) and capacitance-voltage ($C-V$) measurements, deep level transient spectroscopy and emission spectroscopy [1 – 4]. Corresponding to this, many studies on temperature dependence of barrier height (Φ_b) and the physical mechanism of Fermi level pinning at the metal–semiconductor interface have also been performed [5 – 8]. In these studies, it has been shown that the Fermi level is pinned either by metal induced gap states (MIGS) or defect states at the interface. Thus, the dependence of Φ_b on the temperature can give insight into the physical mechanism of Fermi level pinning at the metal–semiconductor interface. On the other hand, the pressure as well as the temperature dependence of the barrier height has been investigated in order to study barrier height formation and the results of these studies have also been explained by the MIGS model [2, 9 – 11].

In recent years, the time dependence or ageing effect on diode parameters has been investigated by many researchers [12 – 14]. In these studies, the Φ_b values of the air-exposed samples have been found to be higher than those of the reference diode. In other words, ageing has increased the ideality factors n while decreasing the Φ_b values of the samples with increasing ageing time. The same results have been also obtained on the polypyrrole/p-Si/Al structure by Saglam et al. [15] and it has been seen that n slowly decreased from 2.00 to 1.93 with increasing ageing time. In addition, both Φ_b and the series resistance R_s increased with increasing ageing time. To sum up, although an enormous amount of information on the time dependence of diode parameters of Schottky diodes has been gained, little is known about the effect of time on these diodes under hydrostatic pressure. There has been no report in the past on the time-dependent characteristics of Schottky barrier diodes under hydrostatic pressure. In [16], Çankaya et al. showed that the pressure treatment improves the rectifying properties of Au/n-GaAs Schottky diodes. Additionally, the $I-V$ characteristics were also measured at different time periods after the hydrostatic pressure was removed. The results showed that the $I-V$ characteristics remain unchanged and coincide with the ones obtained at 1 kbar. We report our studies on Pb/p-Si diodes and how the characteristic parameters such as Φ_b and n of the diode change with increasing time under hydrostatic pressure.

2. Experimental Procedure

Metal/p-type Schottky diodes were prepared, using mirror cleaned and polished p-type silicon wafers with [100] orientation and 5 – 10 Ω cm resistivity. The wafer was chemically cleaned and the ohmic contact was made by evaporating aluminium on the back of the substrate, followed by a temperature treatment at 575 °C for 3 min in an N_2 atmosphere. The native oxide on the front surface of the substrate was removed in a HF : H_2O (1 : 10) solution, and the wafer was finally rinsed in deionised water for 30 s. For metal/p-type Si Schottky structures, the contact metal, lead, with diameters of about 1 mm on the front surface of the wafer was deposited by thermal evaporation. All evaporation processes were carried out in vacuum maintained by a turbomolecular pump at about 10^{-6} mbar pressure.

$I-V$ measurements in the hydrostatic pressure range of 1, 2, and 4 kbar were made by electrical connections from the cell to the diode. In order to investigate the effect of time on the diode parameters of the Pb/p-Si Schottky barrier diode, $I-V$ measurements with and without pressure were performed by the use of a HP 4140 picoammeter/voltage source at room temperature, in the dark and repeated at immediate, 15, 30, 60, and 120 min time intervals.

3. Results and Discussion

The $I-V$ data were analyzed under the assumption that the dominant current transport mechanism is the thermionic emission. According to this theory, the $I-V$ relationship of a Schottky diode is given by [17 – 19]

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

where q is the electronic charge, V the applied voltage, and n the ideality factor, which is given by

$$n = \frac{q}{kT}\left[\frac{\partial V}{\partial(\ln I)}\right]. \quad (2)$$

In (1), I_s is the saturation current derived from the straight line intercept of ln I at $V = 0$, and is given by

$$I_s = AA^*T^2 \exp\left[\frac{-q\Phi_b}{kT}\right], \quad (3)$$

where A is the effective diode area and A^* the effective Richardson constant of 32 $A/cm^2 K^2$ for p-type Si. Figures 1a–c show the forward and reverse bias $I-V$ characteristics of the Pb/p-Si Schottky diode measured at immediate, 15, 30, 60, and 120 min for 1, 2, and 4 kbar hydrostatic pressure, respectively. It is evident that the thermionic emission assumption is valid except in the high current region. On the basis of the well-known thermionic emission theory, the Φ_b values were calculated with the help of (3) from the y-axis intercepts of the semi-logarithmic forward bias $I-V$ plots, and the values of n were obtained using (2) in the linear region of these plots, indicating that the series resistance effect in the linear region is not important (Fig. 1). From these curves, the Φ_b values and the value n for Pb/p-type Si diodes have been calculated at 0 kbar as 0.621 eV and 4.98, respectively. The obtained Φ_b values agree remarkably well with those obtained by the other researchers [20 – 22] who have studied Pb/p-Si Schottky diodes, while the obtained n values are different. In the present study, the obtained n values indicate that the diodes obey a metal-interface layer-semiconductor configuration rather than ideal Schottky barrier diodes. For ideal Schottky barrier diodes, n equals to 1. Our n values are considerably larger than 1. This discrepancy is ascribed to the presence of a bias dependent Φ_b, an insulating layer on the organic semiconductor, and the interface states at a thin oxide between the metal–semiconductor or generation-recombination currents within the space region. In our study, as seen in Table 1, the values of the ideality factor n obtained from Figure 1 have approximately been unchanged with increasing time for every hydrostatic pressure value. On the other hand, the Φ_b value slightly increases with in-

Table 1. Diode parameters obtained from $I-V$ characteristics of the Pb/p-Si diode as a function of time under different hydrostatic pressure.

Pressure	1 kbar		2 kbar		4 kbar
	ϕ	n	ϕ	n	ϕ
Immediately	0.629	4.93	0.652	4.01	0.666
15	0.631	4.89	0.655	3.96	0.667
30	0.631	4.91	0.660	3.97	0.669
60	0.646	4.88	0.663	3.98	0.672
120	0.663	4.90	0.671	3.98	0.680

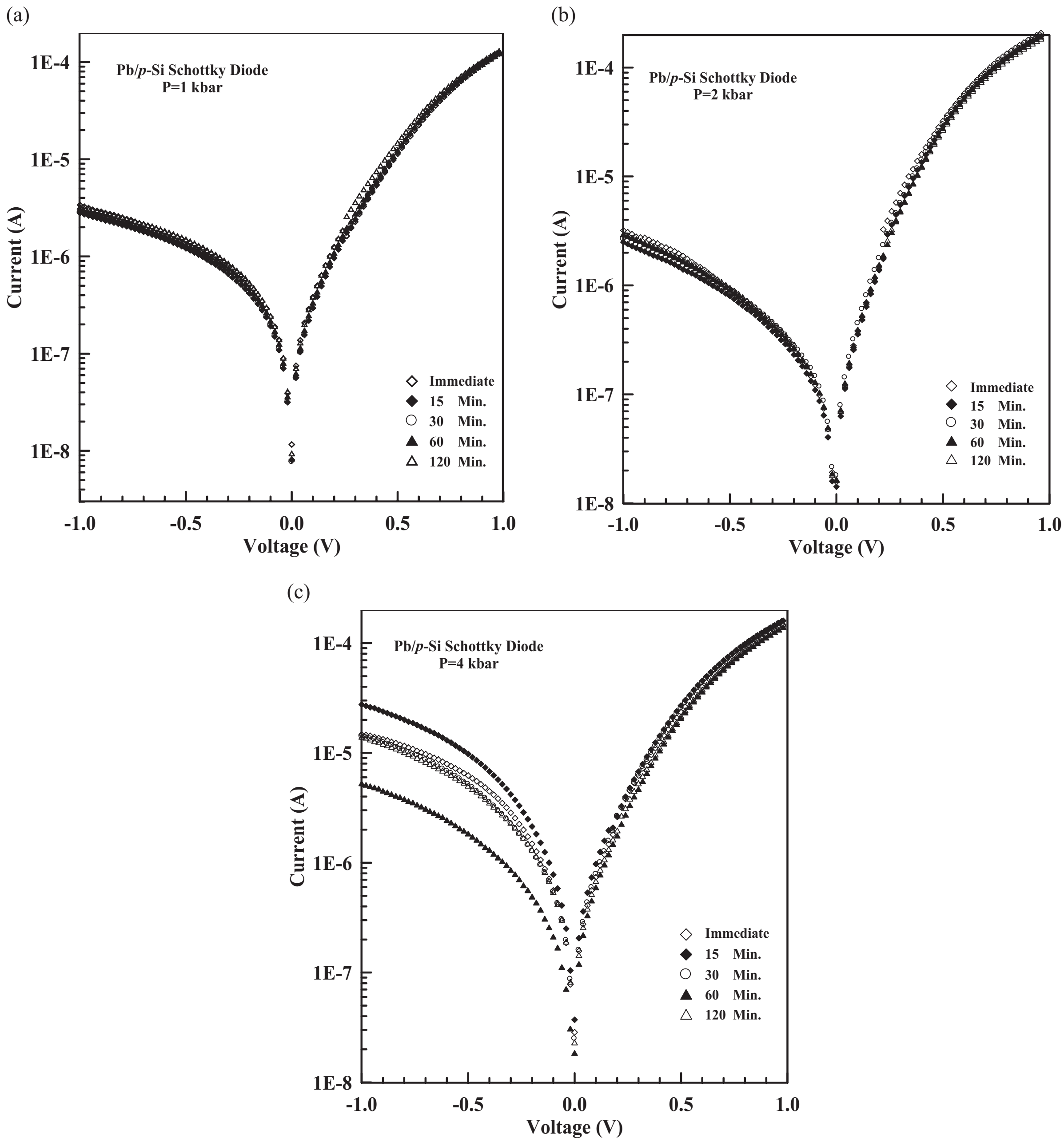

Fig. 1. Forward and reverse bias current–voltage characteristics of the Pb/p-Si diode as a function of time under pressure, (a) 1, (b) 2, and (c) 4 kbar.

creasing time at every hydrostatic pressure. Thus, we can say that it characteristic parameters, such as barrier height and ideality factor, do not change with time seriously, these structures can be used for a long time under a constant hydrostatic pressure. Meanwhile, the slow increase of Φ_b is due to the presence of the interfacial layer on the p-Si surface indicated by a high ideality factor. It is well known that the presence of the interfacial layer on the p-Si surface in the diodes causes the reverse current to increase with increasing reverse bias as a result of the increasing voltage dropping across the interfacial layer and thus cause the effective barrier height to decrease with increasing reverse bias. Furthermore, the Fermi level for the majority carriers rises on the semiconductor side when the diode is biased in the forward direction. Most of these carriers will be injected directly into the metal, forming a thermionic emission current, while some of them are trapped by the interface states. This charge-capture process results in an increase in the effective barrier height [15]. In [12], the time-dependent (ageing) behaviour of Pb/p-Si Schottky diodes (air exposed samples) has been investigated at room temperature by $I-V$ and $C-V$ measurements. In this study, it has been found that the n value increases while the Φ_b value decreases with increasing ageing time by $I-V$ measurements due to passivation of the intrinsic surface states on the cleaned silicon surface. In addition, Özdemir et al. [13] showed that Φ_b and n for a polymer-semiconductor structure can change with time due to change in the oxide film depending on the exposing time of the surfaces (i.e. depending on the oxide layer thickness). Moreover, as seen from Table 1, the n values decrease with increasing hydrostatic pressure. So it can be said that the diode quality improves with the increasing hydrostatic pressure.

Now let us consider the relation between Φ_b and hydrostatic pressure in Pb/p-Si Schottky diodes. It is evident from Table 1 that the Φ_b values increase with increasing hydrostatic pressure at a given time. In the literature, it has been pointed out that many factors may be responsible for variations of Φ_b [23–25]. Some authors [26, 27] have explained these variations by using Fermi level pinning at the metal–semiconductor interface. The unified defect model by Spicer et al. [28] proposed that fabrication-induced defects are responsible for the Fermi level pinning at the metal–semiconductor interface. In contrast to this, metal induced gap states (MIGS) may be considered to be the operative physical mechanism which determines the barrier heights [29, 30]. If the Fermi level pinning is due to MIGS, then the pressure dependence of Φ_b is governed by the pressure dependence of the fundamental band gap of silicon. In our study, the variation in Φ_b with pressure was fitted to the equation

$$\Phi_b(P) = \Phi(0) + \alpha P \tag{4}$$

with $\alpha = 9.2$ meV/kbar (= 92 meV/GPa) the pressure coefficient of Φ_b. In [31, 32] the pressure dependence of the band gap of p-Si is given as 0.5 meV/GPa. This value is much smaller than the calculated pressure coefficient of Φ_b for Pb/p-Si Schottky diodes. Therefore, in the current study we cannot say that the Fermi level is a reference level which is pinned to the valence band maximum with increasing pressure as indicated in the MIGSs model. We believe that the pressure dependence of Φ_b can be explained as due to lateral inhomogeneities in local Φ_b. In [33], the variation of apparent Φ_b with temperature has been explained considering lateral inhomogeneities in Φ_b in nanometer scale lengths at the metal–semiconductor interface when the temperature coefficient of Φ_b is not explained by the MIGS model. Corresponding to this, in many studies [10, 33–38], it has been shown that the temperature and the hydrostatic pressure introduce the same effect on the diode characteristics such as Φ_b and n.

4. Conclusion

In summary, Pb/p-Si Schottky diodes have been fabricated and Schottky diode parameters such as n and Φ_b have been calculated as a function of hydrostatic pressure and time using the $I-V$ characteristics. These values, Φ_b and n, are found to be 0.621 eV and 4.98 at 0 kbar, respectively. The n values remain unchanged whereas the Φ_b increases with increasing time. In addition, the results obtained from $I-V$ characteristics of Pb/p-Si diodes showed that the pressure treatment improves the rectifying properties of the diodes. The barrier height increases with increasing hydrostatic pressure with a linear pressure coefficient, which is higher than the pressure coefficient of the silicon fundamental band gap.

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