Physica B 406 (2011) 771–776

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

On the energy distribution profile of interface states obtained by taking into account of series resistance in $Al/TiO_2/p$–Si (MIS) structures

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ARTICLE INFO

Article history:
Received 2 June 2009
Received in revised form
16 October 2009
Accepted 23 November 2010
Available online 1 December 2010

Keywords:
Thin films
Sol–gel growth
Electrical properties
Surface properties

ABSTRACT

The energy distribution profile of the interface states (N_{ss}) of $Al/TiO_2/p$–Si (MIS) structures prepared using the sol–gel method was obtained from the forward bias current–voltage (I–V) characteristics by taking into account both the bias dependence of the effective barrier height (ϕ_e) and series resistance (R_s) at room temperature. The main electrical parameters of the MIS structure such as ideality factor (n), zero-bias barrier height (ϕ_{b0}) and average series resistance values were found to be 1.69, 0.519 eV and 659 Ω, respectively. This high value of n was attributed to the presence of an interfacial insulator layer at the Al/p–Si interface and the density of interface states (N_{ss}) localized at the Si/TiO_2 interface. The values of N_{ss} localized at the Si/TiO_2 interface were found with and without the R_s at 0.25-E_v in the range between 8.4×10^{13} and 4.9×10^{13} eV^{-1} cm^{-2}. In addition, the frequency dependence of capacitance–voltage (C–V) and conductance–voltage (G/ω–V) characteristics of the structures have been investigated by taking into account the effect of N_{ss} and R_s at room temperature. It can be found out that the measured C and G/ω are strongly dependent on bias voltage and frequency.

1. Introduction

Insulators layers play a significant role in modern device technology. In particular, the Metal–Semiconductor (MS) structures have important applications in bipolar integrated circuits such as microwave detectors, varactors and field-effect transistors. Electrical characteristics of Metal–Insulator–Semiconductor (MIS) structures are influenced by various non-idealities such as formation of and insulator layer and the energy distribution profile of interface states at the metal/semiconductor interface, series resistance and inhomogeneous Schottky barrier heights. In MIS structures, metal and semiconductor remain separated by an insulating layer and there is a continuous distribution of surface states at the semiconductor/insulator interface [1,2]. Although there are a vast number of reports on the experimental studies investigating electrical characteristics parameters, such as the ideality factor, barrier height, series resistance and surface states in MS and MIS structures, satisfactory understanding of all details has not been achieved yet [3–13].

Recently, insulator layers that form on Si, such as Si_3N_4 [7], SnO_2 [4] and TiO_2 [14] films have been investigated as a potential material to replace silicon-dioxide (SiO_2). The main advantages of these films are low densities of the surface states and high dielectric permittivity when compared to SiO_2. The titanium dioxide (TiO_2) thin films are extensively studied due to their interesting chemical, optical and electrical properties. Various methods have been employed to prepare TiO_2 thin films, among which are sputtering [15], e-beam evaporation [16], chemical vapor deposition [17] and sol–gel process [18,19]. The sol–gel method is one of the most promising methods since optical and other properties of thin films can be easily controlled by changing the solution composition and deposition condition.

In this study; the energy distribution profile of interface states was obtained from the forward bias I–V characteristics by taking into account the series resistance and bias dependence of the effective barrier height of $Al/TiO_2/p$–Si MIS structure. Other main diode parameters such as ideality factor (n), zero-bias barrier height (ϕ_{b0}), doping concentration (N_A) and depletion layer width (W_D) of $Al/TiO_2/p$–Si MIS structure are also determined at room temperature. Furthermore, the frequency dependence of C–V and G/ω–V curves under both reverse and forward bias have been studied to experimentally investigate $Al/TiO_2/p$–Si MIS structures by considering the N_{ss} and R_s effects. Experimental results show that both N_{ss} and R_s are important parameters that influence the electrical characteristics of MIS structures.

2. Experimental details

In order to prepare a TiO_2 solution, firstly, 1.2 ml of titanium tetraispropoxide [$Ti(OC_3H_7)_4$, Merck] was added in 15 ml of ethanol [C_2H_6O, Merck] and the solution was kept in a magnetic mixture for 1 h. Then 5 ml of glacial acetic acide [$C_2H_4O_2$, Merck]

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doi:10.1016/j.physb.2010.11.078

and 10 ml of ethanol were added in the solution and after each additive component was added, it was mixed in the magnetic mixture for 1 h. As a final step, 1.5 ml trietilamine [$(S_2H_5)_3N$, Merck] was added in the solution and the final solution was subjected to the magnetic mixture for 3 h.

A lot of metal–insulator–semiconductor (Al/TiO_2/p–Si) structures were fabricated on the 5-inch diameter float zone ⟨1 1 1⟩ p-type (boron-doped) single crystal silicon wafer with a thickness of 600 μm and a resistivity of 5–10 Ω cm. For the fabrication process, Si wafer was degreased through RCA cleaning procedure [i.e. a 10-min boiling in $NH_4OH+H_2O_2+6\cdot DI$ (18 MΩ de-ionised water), which was followed by a 10-min boiling in HCl+H_2O2+6 · DI] [20]. Next, it was subjected to the drying process in N_2 atmosphere for a prolonged time. Following the drying process, high-purity aluminium (99.999%) with a thickness of 1500 Å was thermally evaporated from the tungsten filament onto the whole back surface of the Si wafer under the pressure of 10^{-7} Torr. In order to obtain a low-resistivity ohmic back contact, Si wafer was sintered at 580 °C for 3-min in N_2 atmosphere. The native oxide on the front surface of the substrate was removed in HF:H_2O (1:10) solution and finally, the wafer was rinsed in de-ionised water for 30 s before forming an organic layer on the p-type Si substrate.

The dipping process was performed using a home-made motorized unit and each sample was dipped into the solution 5 times. After each cleaned p-type silicon crystal was dipped into the solution, one substrate of alloy forming on the surface of Si wafer was cleaned with ethanol. After each dipping process, samples were subjected to repeated annealing processes at the temperature of 300 °C for a 5-min period. Finally, the samples were post-annealed at the temperature of 500 °C for 1 h.

In order to obtain a rectifying contact on the front surface of p–Si coated with TiO_2, a high-purity aluminium layer was coated on the surface in a high vacuum under the pressure of 10^{-7} Torr. The structure of Al/TiO_2/p–Si/Al (MIS) is given in Fig. 1. The interfacial insulator layer thicknesses were estimated to be about 63 Å by spectroscopic ellipsometry (VASE M2000, Woolam). The current–voltage (*I–V*) measurements were performed by the use of a Keithley 2420 programmable constant current source. The forward and reverse bias capacitance–voltage (*C–V*) and conductance–voltage (*G–V*) measurements were performed in the frequency range 30 kHz–1 MHz by using a HP 4192 A LF impedance analyzer (5 Hz–13 MHz) and the test signal of 50 mV_{rms}. All measurements were carried out at the room temperature and in the dark.

3. Results and discussion

3.1. Current–voltage (I–V) characteristics

When a Metal–Semiconductor (MS) structure with the series resistance (R_s) is considered, according to the Thermionic Emission (TE) theory, it is assumed that the relation between the applied forward bias voltage V $(V \geq 3kT/q)$ and the current I is expressed as [1,2,21]

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

where I_0 is the reverse saturation current and is described as

$$I_0 = AA^*T^2\exp\left(-\frac{q\phi_{b0}}{kT}\right) \tag{2}$$

where k, n, R_s, V, q, T, A, A^* and ϕ_{b0} are the Boltzmann constant, ideality factor, series resistance, the applied voltage, the electron charge, the temperature in Kelvin, the diode area, the effective Richardson constant (32 A/cm^2 K2 for p-type Si) and zero-bias barrier height, respectively.

Forward and reverse bias ln *I–V* characteristics of the Al/TiO_2/p–Si (MIS) structure at room temperature is given in Fig. 2. As can be seen in the figure, the *I–V* characteristics of the Al/TiO_2/p–Si (MIS) structure exhibit a good rectifying behavior. The rectification ratio has a factor of 5223 achieved between the reverse and forward bias current at ±2 V, at which voltage the reverse bias current saturates. The zero-bias barrier height (ϕ_{b0}) and the ideality factor (n) were determined by Eqs. (1) and (2), and are presented in Table 1. The high values of ideality factor can be attributed to effects of the bias voltage drop across the interfacial insulator layer.

Series resistance (R_s) is an important parameter, particularly in the downward curvature of the forward bias *I–V* characteristics at a sufficiently high bias voltage, while the interface states are important in both linear (at intermediate bias voltage) and non-linear regions of *I–V* curves. In this study, the values of the series resistance (R_s) was evaluated from the forward bias *I–V* data at the high bias voltage region (non-linear region) using the method developed by Cheung and Cheung [8]. Cheung functions are given as

$$\frac{dV}{d(\ln I)} = IR_s + n\left(\frac{kT}{q}\right) \tag{3a}$$

$$H(I) = V + n\frac{kT}{q}\ln\left(\frac{I}{AA^*T^2}\right) = n\phi_b + IR_s \tag{3b}$$

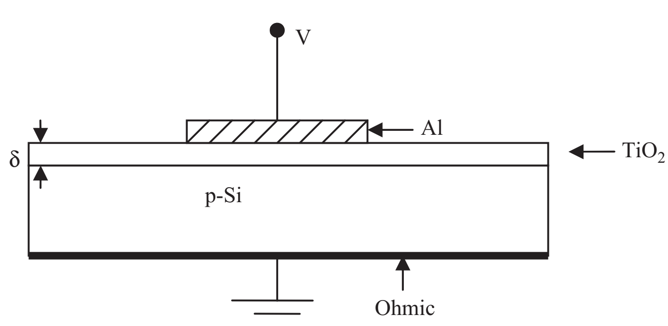

Fig. 1. Schematic diagram of Al/TiO_2/p–Si (MIS) structure.

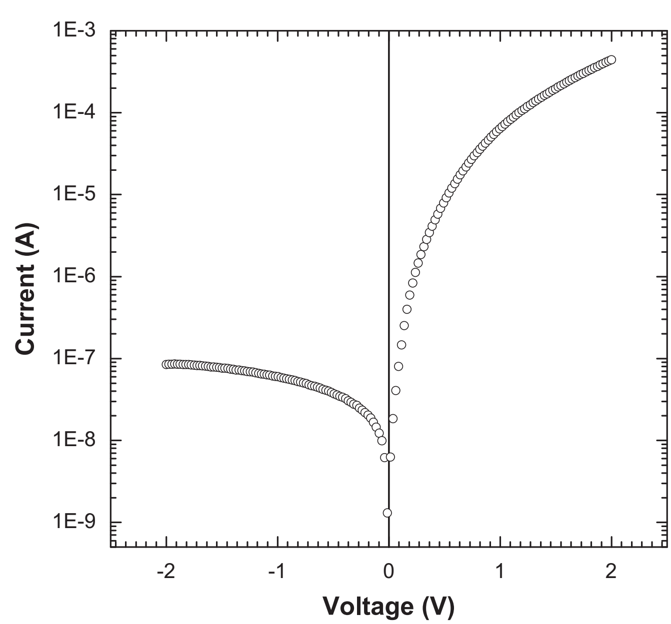

Fig. 2. Forward and reverse bias *I–V* characteristics of Al/TiO_2/p–Si (MIS) structure at room temperature.