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Double Gaussian distribution of barrier height for FeCrNiC alloy Schottky contacts on *p*-Si substrates

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ABSTRACT

The electrical properties of Schottky contact with a quadripartite alloy FeCrNiC on *p*-Si have been investigated in the temperature range of 80–320 K, for the first time. An abnormal decrease in the apparent barrier height ($\varphi_{ap.}$) and an increase in the apparent ideality factor ($n_{ap.}$) with a decrease in the temperature were elucidated by the current–voltage (*I–V*) characteristic of the FeCrNiC/*p*-Si structure. The conventional Richardson plot exhibits non-linear behaviour at temperature below 180 K with the linear portion to be used for the calculation of activation energy and Richardson constant (A^*) as 0.352 eV and 8.3×10^{-3} A K^{-2} cm^{-2}, respectively. The observed anomalies were explained on the basis of the thermionic emission (TE) theory by incorporating the concept of inhomogeneous multiple barriers at Metal–Semiconductor (MS) interface. It has been seen that the apparent barrier height $\varphi_{ap.}$ exhibits double Gaussian distribution (DGD) feature with the mean BH ($\bar{\phi}_{b0}$) of 0.695 and 0.646 eV, accompanied by their standard deviations (σ_0) of 0.082 and 0.070 eV in 320–180 K and 180–80 K regions, respectively. These values of the $\bar{\phi}_{b0}$ have been confirmed with the modified Richardson plot $[\ln(J_0/T^2) - (q^2\sigma_0^2/2k^2T^2)$ vs. $1/T]$ as 0.690 eV and 0.633 eV at the demarcated temperature regions, respectively. Richardson constant A^* has also been calculated from the modified Richardson plots as 33.43 A K^{-2} cm^{-2} and 28.47 A K^{-2} cm^{-2} that belong to two distinct temperature ranges. Their average value exactly matched the theoretical value of 31.6 A K^{-2} cm^{-2} for the holes in *p*-type Si. Our results confirm the predictions of the multiple GD approach of nanoscale spatial BH inhomogeneities at the MS interface.

1. Introduction

Reliable and well-controlled electrical contacts are necessary for a better understanding of the transport properties of plenty of inorganic/organic semiconductors. Metal–Semiconductor (MS) contacts are of great importance since they are an essential part of the known semiconductor devices such as radio frequency detectors, phototransistors, field effect transistor, heterojunction bipolar transistors, quantum confinement devices, light emitting diodes, solid-state lasers and solar cells. They can behave either as a Schottky Barrier (SB) or as an ohmic contact dependent on the features at the MS interface [1,2]. Schottky barrier diodes (SBDs) have been widely used as critical components in the microelectronics industry due to their low threshold voltages and fast switching actions at high frequencies [1]. Different parameters, such as barrier height (BH), ideality factor n, serial resistance R_s and surface morphology qualify the electronic properties of these devices. The Thermionic Emission (TE) theory is usually used to extract the SBD parameters [2]; however, numerous works have been reported on the anomalies observed at low temperatures [3–7]. Therefore, in order to fully comprehend the nature of the electrical properties of SBDs, investigating their temperature-dependent behaviours is of crucial importance. The apparent ideality factor ($n_{ap.}$) and apparent BH ($\varphi_{ap.}$) values which have been determined through the *I–V* measurements are found to be strongly temperature dependent [3–7]. In general, $\varphi_{ap.}$ decreases with the decreasing temperature, while $n_{ap.}$ increases. The decrease in the apparent BH at low temperatures leads to non-linearity in the conventional Richardson plot. Recently, these anomalies have been explained satisfactorily by incorporation of the concept of BH inhomogeneity, which consists of a Gaussian distribution (GD) function having a mean BH and their standard deviations under the TE theory [4–9].

Up to now, various metals such as Al, Sn, Fe, Ni, Ti, Co, Cr, Mo and their alloys [4–9] have been studied to form metal/*p*-Si Schottky contacts. However, to the best of our knowledge, the FeCrNiC

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quadripartite alloy system has not been tested yet. Therefore, it would be interesting to investigate the contact properties of FeCrNiC alloy on *p*-Si.

In this study, the electrical characterization as a function of temperature for FeCrNiC alloy SBDs on *p*-type Silicon was carried out in the temperature range of 80–320 K. The temperature dependence of the diode parameters were systematically investigated in order to elucidate the origin of anomalous behaviour of BH and ideality factor and the significant underestimation of Richardson's constant.

2. Experimental procedure

FeCrNiC/*p*-Si SBDs were prepared on a mirror cleaned and polished *p*-type Si wafers with (1 0 0) orientation and with the resistivity of 6.0–8.0 Ω-cm. For the fabrication process, a Si wafer was chemically cleaned by using the standard RCA cleaning procedure. Aluminium was evaporated on the back surface of the substrate and then annealed in a tube furnace in forming gas (N_2) at 570 °C for 3 min to form an ohmic contact. The Schottky contacts were formed by evaporating FeCrNiC alloy with the ratio of (71:18:8:0.2) as dots with 600 µm diameter onto the front surface of the *p*-Si wafer through a molybdenum shadow mask. The deposition processes were carried out in the Leybold-Heraeus Univex 300 vacuum-coating unit under the pressure of 3.0×10^{-6} mbar.

A computer interfaced Keithley 487 Picoammeter/Voltage Source was used to collect the *I–V* data of the devices. Low temperature measurements (at the 80–320 K regions, with 10 K steps) were performed at the ARS HC-2 closed-cycle helium cryostat by mounting the device onto the specially designed probe station coupled with the cold finger. Lake Shore 331 auto-tuning controller with a high-accuracy of ±0.1 K was used to control of the device temperature under the test.

3. Results and discussion

The forward *J–V* characteristics of most Schottky diodes based on the TE theory can be expressed as [1,2]:

$$J = J_0 \exp\left(\frac{qV_d}{nkT}\right)\left[1 - \exp\left(-\frac{qV_d}{kT}\right)\right], \tag{1}$$

where $V_d (= V - A_{eff} R_S J)$ is the voltage drop across the diode. Saturation current density J_0 is given as:

$$J_0 = A^* T^2 \exp\left(-\frac{q\varphi_{b0}}{kT}\right) \tag{2}$$

In the above equations, A^* is the Richardson constant ($31.6\ \mathrm{A\,cm^{-2}\,K^{-2}}$) for the holes in *p*-type silicon [1,2], A_{eff} is the effective diode area, R_S is the series resistance, $\varphi_{b0} (= \varphi_b(V = 0))$ is the zero-bias or apparent BH, $n (= 1/(1 - \beta))$ is the ideality factor, $\beta (= \partial\varphi_b/\partial V)$ is the change in the BH with bias voltage and the other symbols have their usual meanings.

From the Eq. (1), the ideality factor of the device can be determined experimentally using $\ln[J/\{1 - \exp(qV_d/kT)\}]$ vs. V_d plot. If n is constant, the plot should be a straight line with a slope giving the q/nkT, even for $V \langle 3kT/q$. However, more usually β is not constant and the plot of $\ln[J/\{1 - \exp(qV_d/kT)\}]$ vs. V_d is not linear. Hence, for $V \rangle 3kT/q$, n is expressed as [1,2]:

$$\frac{1}{n} = \frac{kT}{q}\frac{d(\ln J)}{dV} \tag{3}$$

Fig. 1 shows the forward- and reverse bias *I–V* characteristics of a typical FeCrNiC/*p*-Si SBD in the temperature range 80–320 K, in steps of 10 K. As can be seen in the figure that *I–V* characteristic of the FeCrNiC/*p*-Si SBD is temperature dependent and has a satisfactorily rectifying property in this temperature region. It is also clear that *I–V* plots shifted towards to higher bias region, and the reverse saturation current decreased with decrease in the temperature as predicted by the TE theory. Moreover, temperature dependent *I–V* characteristics are linear in the semi-logarithmic scale over several orders of current, although they deviate from linearity when the applied voltage is sufficiently large. This could be associated with the effect of the interface states and series resistance R_S. Forward bias *I–V* data were used to calculate the serial resistance by using Cheung's functions for each temperature [10]. Average values of the R_S determined from Cheung's functions (not shown in here) are used for constructing the $\ln[J/\{1 - \exp(qV_d/kT)\}]$ vs. V_d plot. Then, the values of the ideality factor n and φ_{b0} are extracted from the slopes and the *y*-axis intercepts at each temperature, respectively. The values of φ_{b0} and ideality factor n range from 0.297 eV to 0.572 eV and 2.703 to 1.099 when the temperature changes from 80 K to 320 K.

The temperature dependence of the ideality factor n and φ_{b0} are given in Fig. 2. As seen in this figure, both n and φ_{b0} are strongly temperature dependent. The ideality factor n increases and the φ_{b0}

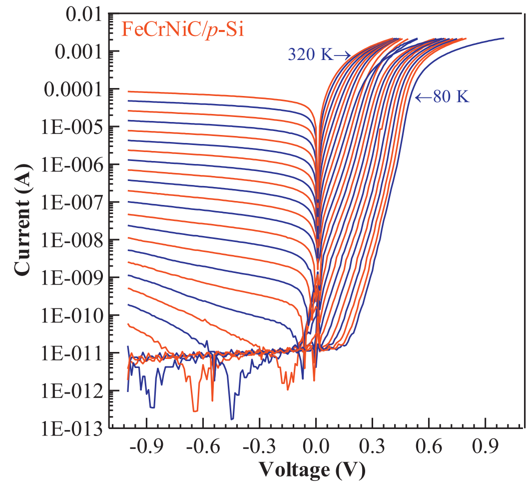

Fig. 1. Experimental forward- and reverse bias *I–V* characteristics of a typical FeCrNiC/*p*-Si SBD in the temperature range of 80–320 K.

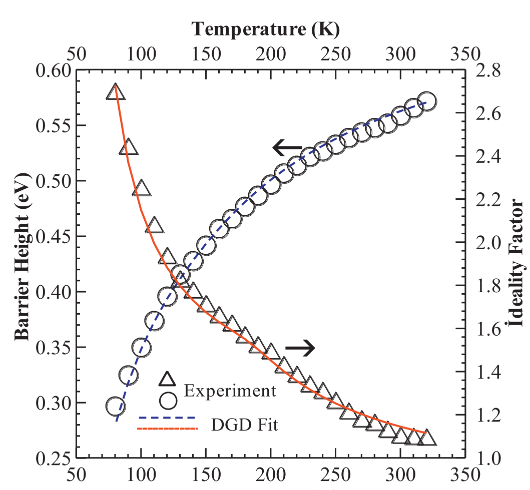

Fig. 2. Temperature dependence of apparent BH and apparent ideality factor for the FeCrNiC/*p*-Si SBD. The continuous dashed and solid curves show estimated values of $\varphi_{ap.}$ and $n_{ap.}$ using Eqs. (9) and (10), respectively.