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Letter to the Editor

ELECTRODE DEPENDENCE OF SPACE-CHARGE-LIMITED CURRENT IN a-Si/c-Si HETEROSTRUCTURES

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Amorphous silicon has been deposited onto crystal silicon forming a-Si/c-Si heterostructures. Nickel and gold electrodes were then evaporated on the a-Si side and DC electrical properties are investigated. It is observed that space-charge-limited conduction prevails; beyond a field of 4.9×10^2 V cm^{-1} in the Au-electrode device near the liquid-nitrogen temperature, and 6.5×10^2 V cm^{-1} in the Ni-electrode device at room temperature. From the results, the density of deep trapping states is estimated at 10^{15} eV^{-1} cm^{-3}.

1. Introduction

The observation of space-charge-limited current in amorphous silicon (a-Si) was reported by den Boer [1], who used the data to determine the density of gap states. Heterojunctions formed by such thin films on crystal silicon (c-Si), first proposed by Dholer and Brodsky [2], have been investigated experimentally by Matsuura et al. [3]. The a-Si/c-Si heterojunction depicts some unusual DC conduction characteristics, due to complexities posed by the gap states in the a-Si as well as the interface, as evidenced by the negative activation energies [4].

2. Experimental details and results

Films of a-Si were deposited by plasma DC glow discharge (GD) onto p-type silicon substrates of 1.8–2.2 Ωcm resistivity. The GD technique has been described elsewhere [5]. For the work presented in this paper, helium rather than nitrogen was used for purging the reactor prior to the SiH_4 discharge. The geometrical configuration of the gas feeder line takes the form of a circular loop with small holes facing the centre (see fig. 1). A fine stainless mesh acts as a grid and is electrically connected to the lower electrode, to enhance deposition rate and improve film quality.

The deposition was carried out at a pressure of 0.2 mbar for 5 h at room temperature, with a discharge voltage of 1.7 kV. The deposition rate is

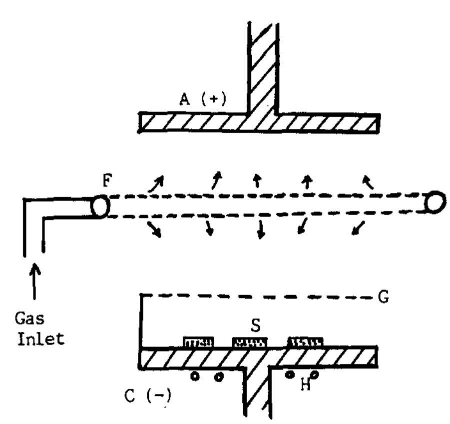

Fig. 1. Schematic diagram of the plasma glow discharge reactor. F is a circular feeder line with a diameter slightly larger than the electrodes, A and C. The grid G is held at the same negative potential as the cathode C. H is the heater and S the c-Si substrates.

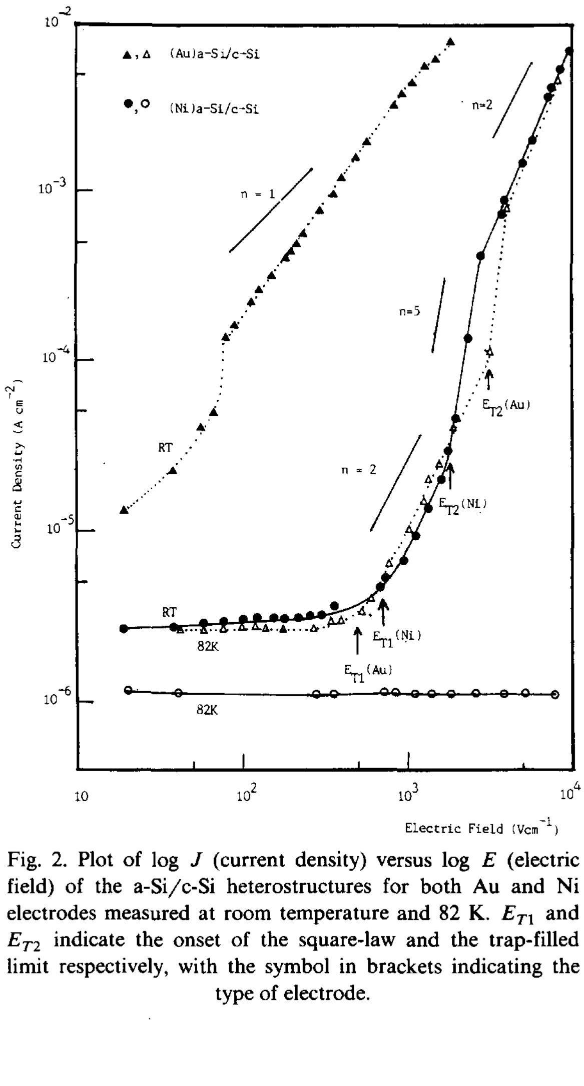

Fig. 2. Plot of log J (current density) versus log E (electric field) of the a-Si/c-Si heterostructures for both Au and Ni electrodes measured at room temperature and 82 K. E_{T1} and E_{T2} indicate the onset of the square-law and the trap-filled limit respectively, with the symbol in brackets indicating the type of electrode.

estimated to be 2.5 Å s^{-1}. The resulting a-Si film was 5.21 μm thick as measured by ellipsometry. An optical gap of 1.93 eV was deduced from optical transmission measurements. Antimony was evaporated on the back of the c-Si while nickel (Ni) and gold (Au) formed circular top contacts on the a-Si with a device area of 0.0346 m^2.

Measurements were taken at room temperature (RT) and 82 K using an Oxford Instrument liquid-nitrogen cryostat and the DC current was registered by a Keithley 485 picoammeter.

Results of the DC conduction are shown in fig. 2, plotted in terms of the current density versus electric field, where negative voltages are applied either to the Ni or Au electrode. It is obvious that there is an immediate difference in the J–E curves of the (Ni)a-Si/c-Si and (Au)a-Si/c-Si heterojunctions.

The latter depict a sharp rise in current for fields below 10^2 V cm^{-1} at RT and beyond this it is almost ohmic with a slope slightly larger than unity. However, the (Ni)a-Si/c-Si structure shows strong saturation up to a field of $E_{T1} \simeq 6.5 \times 10^2$ V cm^{-1}, followed by a square-law relationship up to $E_{T2} \simeq 1.6 \times 10^3$ V cm^{-1}, see table 1. A power-law regime exists beyond this where $n \simeq 5$. A somewhat similar behaviour is observed for the (Au)a-Si/c-Si heterostructure at 82 K temperature with values of $E_{T1} \simeq 4.9 \times 10^2$ V cm^{-1} and $E_{T2} \simeq 3.0 \times 10^3$ V cm^{-1}. Such phenomena, however, are not seen in the (Ni)a-Si/c-Si heterostructures

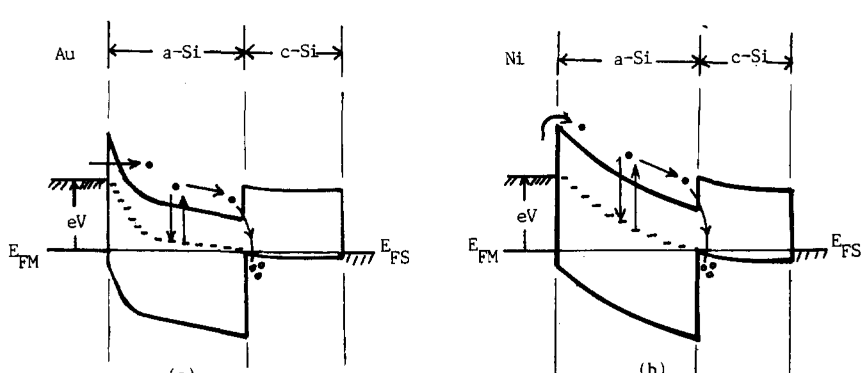

Fig. 3. Schematic band diagram representation of the heterostructures in a situation where space-charge conduction occurs for (a) (Au)a-Si/c-Si at 82 K, and (b) (Ni)a-Si/c-Si at RT.

Table 1
Classification of the two threshold voltages (E_{T1} and E_{T2}), the saturation current J_{sat} and the average density of gap states $\overline{N}_t$ for both types of heterostructures

Hetero-junction	T (°K)	E_{T1} (V cm^{-1})	E_{T2} (V cm^{-1})	J_{sat} (A cm^{-3})	$\overline{N}_t$ (eV^{-1} cm^{-3})
(Au)a-Si/c-Si	82	4.9×10^{2}	3.0×10^{3}	2.7×10^{-6}	1.9×10^{15}
(Ni)a-Si/c-Si	300	6.5×10^{2}	1.6×10^{3}	3.0×10^{-6}	4.9×10^{14}
	82	–	–	1.1×10^{-6}	–

where a constant current of 1.1×10^{-6} A cm^{-2} is recorded over the entire electric field of interest.

It is not yet clear at this point as to how the conduction band offset between the a-Si and c-Si at the interface should behave. The high ohmic current present in the (Au)a-Si/c-Si heterostructure at room temperature, on the assumption that the Au electrode is non-blocking to electrons [6], can lead to two plausible mechanisms. Firstly, the interface barrier to electrons, if it exists, is minimal, and secondly, holes in the c-Si side could enhance interface recombination with electrons, provided the energy bands of the c-Si are "accumulated".

Rectification of the a-Si surface by the Ni electrode at RT explains the saturated current characteristic for fields less than E_{T1}(Ni), an indication of insufficient electrons coming from the electrode, possibly due to a large barrier height. Hence this is a good criterion for space-charge-limited conduction to occur at higher fields, i.e. greater than E_{T1}(Ni), thus leading to the trap-filled limit case at E_{T2}(Ni).

Following the procedure of den Boer [1], an estimate of the average density of gap states $\overline{N}_t$ close to the Fermi level in the a-Si are estimated. In this case, it is applicable only for electric fields greater than E_{T2}(Au) at 82 K and E_{T2}(Ni) at RT and the corresponding values deduced for $\overline{N}_t$ are 1.9×10^{15} eV^{-1} cm^{-3} and 4.9×10^{14} eV^{-1} cm^{-3} respectively.

Figure 3 shows the schematic band diagram for the two heterostructures in a situation where space-charge conduction occurs. For the (Au)a-Si/c-Si structure it is proposed that electron injection from the metal electrode occurs by thermally-assisted tunneling at 82 K. On the other hand, for the (Ni)a-Si/c-Si structure at RT it is proposed that electrons are supplied via thermionic emission.

Taking the form of a thermally activated process, the saturated current density is then

$$J_{sat} \simeq \exp\left(\frac{-W}{kT}\right),$$

where W is the activation energy concerned. By applying the respective values of J_{sat} at RT and 82 K, it is deduced that $W \simeq 9.7$ meV. Such a small energy can mean that electron conduction involves only the gap states of a-Si..

Beyond E_{T2}, electron–hole recombination can be an important factor and this can occur only at the a-Si/c-Si interface, or in the a-Si at some distance away from it, due to holes tunneling from the c-Si. The rise to a power relationship of $n = 5$ is an indication of a trapping-filled limit phenomenon.

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