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ELECTRONIC TRANSPORT THROUGH a-Si:H/a-SiN_x:H SINGLE AND DOUBLE BARRIER STRUCTURES

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Current bumps in the current-voltage characteristics of amorphous semiconductor double barrier structures have previously been associated with a resonant tunneling process through quantized levels in the well region of the structure. We investigate the perpendicular transport through a-Si:H/a-SiN_x:H single (SB) and double (DB) barrier structures grown by glow discharge. Current bumps are observed in the I-V characteristics of both SB and DB structures at 77 K which suggests a different transport mechanism than previously proposed. We propose that the first current bump is simply a transition from a low-field (space-charge-limited) transport mechanism to a high-field (multiple hopping) transport mechanism. The additional bumps are associated with the energy-dependence of the density of localized states in the a-SiN_x:H and a-Si:H.

Perpendicular transport in amorphous semiconductor multilayered structures (a-SC ML) has been studied so far by many groups[1-6]. Quantum confinement effects have been reported by several groups studying the I-V characteristics of double barrier (DB) structures. Miyazaki et al.[1] associated current bumps in the I-V characteristics of doped a-Si:H/a-SiN_x:H DB structures to a resonant tunneling phenomena through quantized levels in their doped amorphous silicon (a-Si:H) well layer. Pereyra et al.[2] also suggested the presence of quantum size effects and showed that current bumps in a-Si:H/a-SiC_x:H DB structures can be accentuated using fast voltage sweep rates (up to 10 V/s) during the acquisition of the I-V curve. Carreño et al.[3] later showed that similar current bumps were observed in a-Si:H/a-SiC_x:H single barrier (SB) structures and structures with rectifying contacts. They explained the dependence of their I-V characteristics on the sweep rate by a capacitive effect instead of a quantum size effect.

However, other groups have explained the perpendicular transport in a-SC ML without considering quantum confinement of the electronic levels. Arce et al.[4] did not observe any current bumps in the I-V curves of their a-Si:H/a-SiN_x:H DB structures. Instead, they observed random telegraphic noise which was associated to the presence of microchannels in their structures. Time-of-flight studies[5,6] have also suggested a dispersive transport mechanism (i.e. multiple trapping) in the well region of a-Si:H/a-SiN_x:H multilayers.

In this paper, we study the perpendicular transport properties of a-Si:H/a-SiN_x:H DB structures. We chose not to dope the a-Si:H well layer since the mobility of doped a-Si:H decreases with dopant concentration[7] indicating an increase in electron scattering which reduces the likelihood of resonant tunneling. We show that the steady-state current bumps observed in both SB and DB structures can

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be explained by a trap-assisted tunneling process. This transport phenomena is very sensitive to the density of localized states in the barrier region and to the density of interface states between the barrier and well regions.

The SB and DB structures were grown on heavily doped crystalline Silicon (c-Si) substrates in a capacitively-coupled rf glow discharge system. The n^+ c-Si acted as the injecting contact to the SB and DB structures. Pure SiH_4 was used during the growth of the undoped a-Si:H layer, while a gas mixture of NH_3/SiH_4 (10:1) was used for the a-SiN$_x$:H layer. An 8% PH_3 in SiH_4 mixture was used for the heavily doped a-Si:H top layer (360 Å thick) which acted as the collecting contact to the structures. The substrate temperature, rf power, and total pressure were held at 300 °C, 10W and 200 mTorr respectively. The glow discharge system was evacuated quickly and purged for 50 min after each nitride layer to a base pressure of ~3 x 10^{-6} Torr. For the SB structures, an 80 Å thick a-SiN$_x$:H barrier was grown on the n^+ c-Si substrate. The DB structure consisted of a 25 Å thick a-Si:H layer placed between two 40 Å thick a-SiN$_x$:H layers. The layer thicknesses for the SB and DB structures were estimated using the growth rate calculated from thicker bulk samples. The dark resistivities of these thick (~0.3 μm) bulk samples were approximately 10^4 Ωcm, 10^{15} Ωcm and 10^9 Ωcm for n^+ a-Si:H, a-SiN$_x$:H and a-Si:H respectively which indicate the good quality of our layers.

The deposition of metal contacts and the mesa definition were performed in a clean-room environment (class 1000). Samples were dipped in diluted HF (1:10) and rinsed in DI H_2O immediately prior to metallization. Titanium (500 Å thick) was used as contact material to the n^+ a-Si:H layer followed by a top layer of 1000 Å of gold. The Au/Ti contact was used as mask during the dry etching of the mesa in a $CF_4 + O_2$ plasma ($[O_2]/[CF_4] = 0.04$). The diameter of the mesa was 610 μm.

A previous XPS study[8] of our a-SiN$_x$:H/a-Si:H interface showed that the interface obtained between near stoichiometric a-SiN$_x$:H (x = 1.4) and a-Si:H was atomically abrupt since subnitride components constituted less than 1% of the interface bonds. The valence-band offset for this interface was also obtained by following a standard analysis of the XPS valence-band spectra[9]. The measured valence-band offset of 1.3 eV is consistent with values previously published for an a-Si:H/a-SiN$_x$:H interface[9]. From the bandgap of the bulk materials, the conduction-band offset was estimated to be 2.0 eV.

Typical I-V characteristics of the SB and DB structures are shown in Figure 1 for 295 K and 77 K. The applied bias shown corresponds to a positive voltage to the Au/Ti top contact. We have verified that all measurements are unaffected by changes in voltage scanning speeds between 10 mV/s and 1 V/s. Therefore, any current bumps in our I-V characteristics can not be associated to capacitive effects similar to those of Carreño et al.[3].

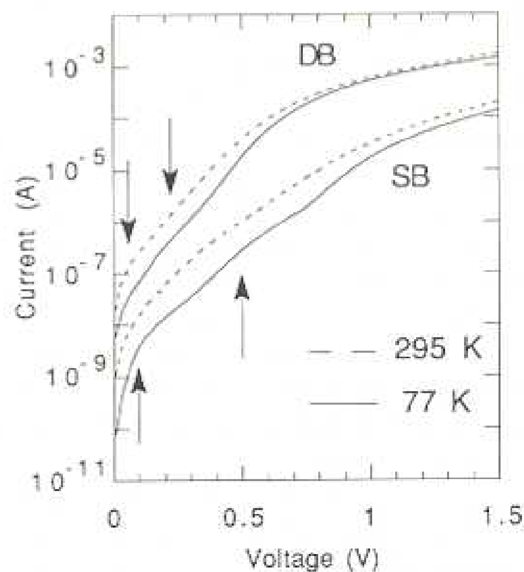

Figure 1: Typical Current-Voltage characteristics of a SB and a DB structure measured at 295 K (dashed line) and 77 K (solid line). The arrows indicate the current bump positions.

The 295 K I-V curves of the SB and DB structures present no important features. The 77 K I-V curves show a rapid increase at low V (V < 0.1V) and a more gradual rise for larger voltages which might suggest the presence of a bump in the I-V curve close to 0.1 V. Miyazaki et al.[1] associated a similar bump at low applied voltages to a resonant tunneling process through the first quantized level of the well layer. However, it is unlikely that this bump near 0.1 V in the I-V curves of our samples can be attributed to a resonant tunneling process since it is seen in almost all I-V curves of both SB and DB structures. We propose that this bump can be explained by a transition from a low-field conduction mechanism to a high-field conduction mechanism.

The low-field transport mechanism in insulating material is known to exhibit ohmic behavior ($I \propto V$) at very low electric fields with an onset of space-charge-limited conduction ($I \propto V^2$) at a critical field of typically 10^3-10^4 V/cm. In comparison, the field across the thin insulating layer (~80 Å) of our SB structures is ~10^5 V/cm at an applied voltage of 0.1 V. Therefore, space-charge-limited currents should predominate at these low applied voltages.

As the field is increased, the transition probability between localized states is increased due to electric field heating of the localized electrons. Furthermore, unoccupied states of higher energy are lowered by the field and can participate in the hopping conduction. Movaghar et al.[10] have shown that this kind of high field transport leads to a field dependence of $\exp(\gamma F^{\alpha})$ with α ~ 0.5 for many different types of density of state distributions (e.g. constant, power law, exponential). As shown in Figure 2, the fit using the V^2-dependence (space-charge-limited) and the $\exp(\gamma F^{\alpha})$-dependence (high-field hopping transport) reproduces quite well the general behavior of the I-V characteristic of the SB structure presented in Figure 1. The best fit was obtained using $\alpha = 0.45$.

Since hopping conduction dominates at high-fields, the fine detail in the high-field region of the I-V curve (V > 0.2V) will be very sensitive to the density of the localized states in the barrier region as well as the density of interface states at the a-Si:H/a-SiN$_x$:H interfaces. As the applied bias is increased, the unoccupied gap states in the barrier which are above the Fermi level are lowered in energy. A strong energy-dependence of these gap state densities will produce structure in the I-V characteristics. Robertson and Powell[11] have shown that the Si dangling bond distribution in a-SiN$_x$:H (ρ ~ 10^{17} cm^{-3}) lies about 2 eV below the mobility edge of the conduction band. If we approximate the voltage-position of the current bump as twice the energy difference between the dangling bond distribution and E_F, the current bump at 0.5V would correspond to a Si-dangling bond distribution located at ~0.25 eV above E_F. This corresponds to ~1.75 eV below E_c of a-SiN$_x$:H and is consistent with the value suggested by Robertson and Powell[11]. In addition to the Si-dangling bond distribution within the a-SiN$_x$:H barrier, the a-Si:H/a-SiN$_x$:H interface states might also contribute to current bumps in the I-V characteristic.

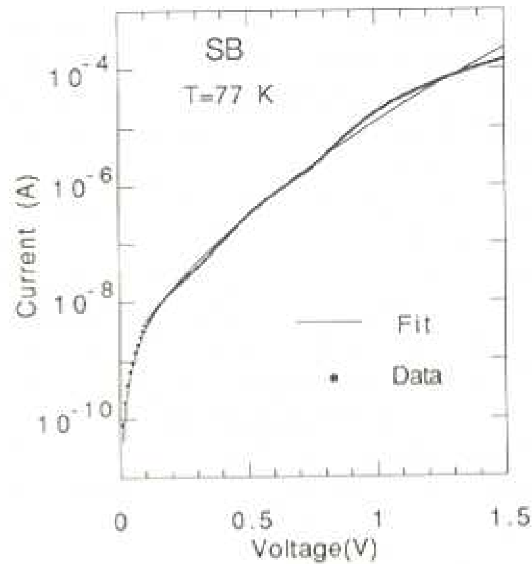

Figure 2: Fit (solid line) of the SB I-V characteristic (points) at 77 K with a multiple hopping model at high applied voltage and a space-charge-limited model at low applied voltage.

The I-V curve of the DB structure (Figure 1) has

current bumps at 0.07 and 0.2 V. Since current bumps are observed in both SB and DB structures, it is unlikely that these bumps result from a resonant tunneling process. As for the SB structure, the first bump can be explained by the transition from a space-charge-limited conduction regime to a high-field hopping mechanism. The additional bump at 0.2 V is likely caused by the energy-dependence in the density of localized states in the barrier regions (Si-dangling bond distribution) or in the distribution of interface states at both a-Si:H/a-SiN$_x$:H interfaces.

The interpretation proposed here for the perpendicular transport in a-Si:H/a-SiN$_x$:H SB and DB structures is consistent with recent time-of-flight studies on similar multilayer structures. Grahn et al.[5] have shown that the transport in the well layer (d > 39 Å) of a-Si:H/a-SiN$_x$:H multilayers is multiple trapping for T > 150K, while at lower temperatures hopping down in energy is the predominant mechanism. Furthermore, Hattori et al.[6] suggest a model based on inter-well tunneling followed by multiple trapping within the well to explain the field-dependence of the electron drift velocity. These results suggest that the carriers in a-Si:H/a-SiN$_x$:H multilayered structures undergo inelastic collisions after travelling a distance less than the well layer thickness. These collisions would destroy the phase coherence necessary for the observation of quantum confinement effects.

In conclusion, we explain the current bumps in the I-V characteristics of SB and DB a-Si:H/a-SiN$_x$:H structures with a combination of transport mechanisms which do not rely on quantum confinement within the a-Si:H well layer of the DB structure. We propose that the first current bump is simply a transition from a low-field (space-charge-limited) transport mechanism to a high-field (multiple hopping) transport mechanism. Since hopping transport increases with the density of hopping sites (i.e. localized states), the additional bumps can be associated to the energy-dependence of the density of localized states in the a-SiN$_x$:H and to the interface state energy distribution.

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