Carrier transport through boron-doped amorphous diamond-like carbon *p* layer of amorphous silicon based *p–i–n* solar cells

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The current transport mechanisms in boron-doped amorphous diamond-like carbon (*p*-*a*-DLC:H) used as part of the *p* layer of hydrogenated amorphous silicon (*a*-Si:H) solar cells are investigated by studying the temperature dependence of the dark current–voltage characteristics of the solar cell. The cell structure is glass/SnO_2/p-a-DLC:H/p-a-SiC:H/i-a-Si:H/n-μc-Si:H/Al. The temperature dependence of the reverse saturation current and the ideality factor shows that carriers transport dominantly over the p-a-DLC:H by thermionic emission at higher temperatures above about 300 K and through the tunneling process by a hopping mechanism in the p-a-DLC:H at lower temperatures. Using the Schottky barrier model, it is shown that the lowering of the Schottky barrier height by inserting the interfacial p-a-DLC:H between the SnO_2 and p-a-SiC:H causes the open circuit voltage and the short wavelength response of the cells to be enhanced. [S0003-6951(99)01730-1]

Boron-doped amorphous diamond-like carbon (p-a-DLC:H) showing a wide-energy-band gap above 3.5 eV has been developed for a *p*-type window layer in hydrogenated amorphous silicon (a-Si:H) based solar cells using a photochemical vapor deposition (photo-CVD) method.[1] The Interfacial thin p-a-DLC:H between the SnO_2 and p-a-SiC:H in the cell with a simple structure of glass/SnO_2/p-a-DLC:H/p-a-SiC:H/i-a-Si:H/n-μc-Si:H/Al has been confirmed to act as a hole emitter to enhance the open circuit voltage (V_{oc}) and the short wavelength response of the cell.[1] However, for the p-a-DLC:H to operate as an efficient *p* layer, photocarriers are expected to tunnel easily by sequential tunneling such as variable range hopping (VRH) through localized states of the p-a-DLC:H or by the quantum mechanical tunneling through the film because the interfacial p-a-DLC:H film has a very high resistivity of about 10^{-8} S/cm. For intrinsic *a*-DLC:H film, the conduction mechanism through the film has been explained by the VRH.[2] However, for the p-a-DLC:H used as a window layer of the *a*-Si:H based solar cell, it has not been well known how photocarriers transport through the film. In this letter, we investigate the carrier transport mechanism through the *p*-*a*-DLC:H of the cell by monitoring the dark current–voltage (*I*–*V*) characteristics as a function of temperature and, in particular, by considering the variation of the ideality factor *(n)* and the reverse saturation current $[J_0(T)]$ that is extracted by extrapolating logarithm *I*–*V* as a function of temperature.

Fabricated solar cells have a simple structure of glass/SnO_2/p-a-DLC:H(0–45 Å)/*p*-*a*-SiC:H(55 Å)/*i*-*a*-Si:H(6000 Å)/*n*-*μc*-Si:H(400 Å)/Al without a *p/i* barrier and a back reflector. The dark *I*–*V* characteristics of the cells were measured in an evacuated liquid nitrogen cryostat (10 mTorr) from 180 to 380 K by using a semiconductor parameter analyzer (HP4145B).

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The dark current density (J_d) of *p*–*i*–*n* *a*-Si:H solar cells is expressed as a function of applied voltage (*V*) by

$$J_d = J_0(T)[\exp(qV/nkT) - 1], \tag{1}$$

where $J_0(T)$ is the saturation current density. The variation of $J_0(T)$ in Eq. (1) with the temperature provides information on the carrier transport mechanism. Figure 1 shows energy band diagrams of the glass/SnO_2/p-a-SiC:H/i-a-Si:H/n-μc-Si:H/Al structure cell (a) and the glass/SnO_2/p-a-DLC:H/p-a-SiC:H/i-a-Si:H/n-μc-Si:H/Al (b) along with three basic transport processes of the cells in a dark state under reverse bias condition: the thermionic emission (process A), the VRH conduction (process B), and quantum mechanical tunneling (process C). For process A, using the thermionic emission theory of the metal/semiconductor Schottky junction, the thermionic emission term in the reverse saturation current can be expressed by[3]

$$J_t(T) \propto T^2 \exp(-q\phi_B/kT), \tag{2}$$

where ϕ_B is the Schottky barrier height, as seen in Fig. 1. For process B, the hopping conduction term in the reverse saturation current is expressed by[4]

$$J_h(T) \propto \exp[-(T_0/T)^{1/4}], \tag{3}$$

where $T_0 = 16/[k\alpha_1^3 N(E_F)]$, α_1^{-1} is the extension of the wave function of the localized electron and $N(E_F)$ is the density of states near the Fermi level. The contribution of process C to the $J_0(T)$ for the cell with the *p*-*a*-DLC:H is not significant because the transmission probability, which is calculated by the standard expression[5] for a square barrier is 0.044, assuming that the thickness of the barrier is 5 Å, the barrier height of the *p*-*a*-DLC:H is 0.4 eV, hole energy is *kT* eV ($T = 300$ K), and the tunneling current is not dependent on temperature.[3] Therefore, the total reverse saturation current is expressed at a certain temperature by

$$J_0(T) = AT^2 \exp(-q\phi_B/kT) + B \exp[-(T_0/T)^{1/4}]. \tag{4}$$

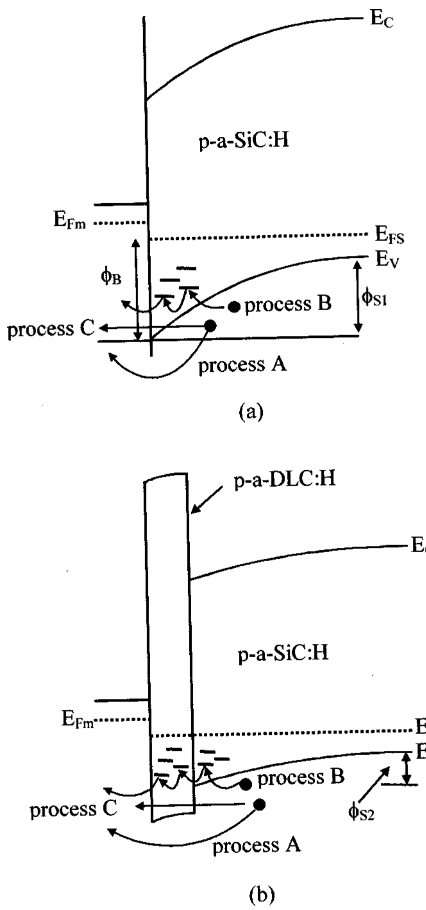

FIG. 1. Two carrier transport processes under reverse bias: process A is thermionic emission, process B is hopping conduction: (a) for the cell with *p*-*a*-SiC:H and (b) for the cell with *p*-*a*-DLC:H/*p*-*a*-SiC:H.

Figure 2 shows the temperature dependence of the $J_0(T)$ of the fabricated solar cells with various *p*-*a*-DLC:H thicknesses. For the cell only with a *p*-*a*-SiC:H, thermionic emission (process A) is dominant in the temperature range above 260 K. Below this temperature, VRH conduction (process B) is dominant. For the cell with a 45 Å-thick *p*-*a*-DLC:H/50 Å-thick *p*-*a*-SiC:H, thermionic emission of the carriers, which are generated from the defects of intrinsic *a*-Si:H (*i*-*a*-Si:H), toward the SnO_2 becomes dominant in the temperature range over ~300 K while VRH conduction is dominant

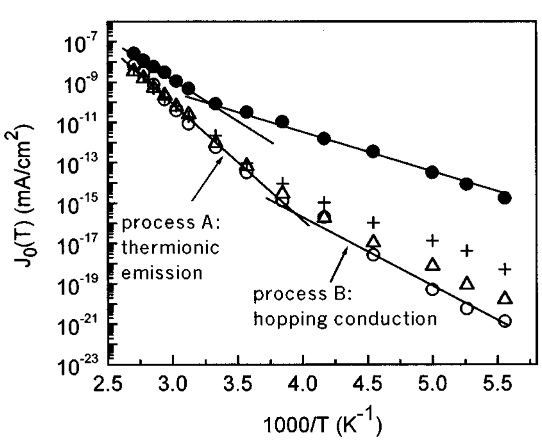

FIG. 2. Temperature dependence of the reverse saturation current $[J_0(T)]$ of the cells with *p*-*a*-DLC:H/50-Å-thick *p*-*a*-SiC:H. The thicknesses of the *p*-*a*-DLC:H layer are 0 Å (○), 5 Å (△), 15 Å (+), and 45 Å (●)

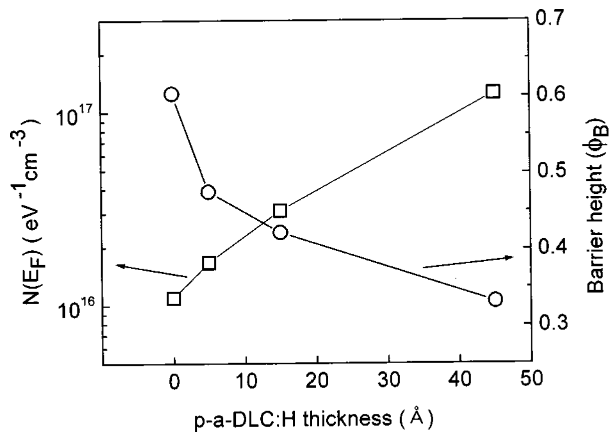

FIG. 3. Density of states near the Fermi level $[N(E_F)]$ and the hole barrier height (ϕ_B) of cells with various *p*-*a*-DLC:H thicknesses.

in the low temperature range below ~300 K. The barrier height empirically obtained by using Eq. (2) is lowered with the increase of the *p*-*a*-DLC:H thickness, as can be seen in Fig. 3, which results in the gradual enhancement of the V_{oc} and the short wavelength response of the cell.[1] This agrees well with the fact that the energy band of the *p*-*a*-SiC:H adjacent to the *p*-*a*-DLC:H would be lifted upward by the Fermi level of the *p*-*a*-DLC:H, and thereby, the interface Schottky barrier (ϕ_{s1}) between the SnO_2 and *p*-*a*-SiC:H, as seen in Fig. 1(a), was replaced by the interface barrier (ϕ_{s2}) formed between the *p*-*a*-DLC:H and *p*-*a*-SiC:H, as seen in Fig. 1(b). The $J_0(T)$ has been thought to be generated by the localized states in the intrinsic bulk layer and *p/i* interface states.[6,7] The $J_0(T)$ in the cells with a *p*-*a*-DLC:H/*p*-*a*-SiC:H increases with the *p*-*a*-DLC:H thickness, as can be known in Fig. 2. This tendency cannot be explained by the generation current of defect states in the *i* layer and the *p/i* interface states. Its additive reverse saturation current with increasing the *p*-*a*-DLC:H thickness originates from the defect generation current in the *p*-*a*-DLC:H. From Figs. 2 and 3, the defect state density of the *p*-*a*-DLC:H is found to be dependent on the thickness. The thickness dependent nonhomogeneous properties at the initial growth of the *p*-*a*-DLC:H can be confirmed by the dependence of the density of states near the Fermi level $N(E_F)$, on the *p*-*a*-DLC:H thickness, which is extracted from Eq. (3) using $\alpha_1^{-1}=5$ Å, as shown in Fig. 3.[2] The defect states of the *p*-*a*-DLC:H are low at the initial deposition stage but they increase exponentially with the thickness, which severely increases the recombination loss in the cell, resulting in the poor fill factor (FF) and short circuit current density (J_{sc}).[1]

Figure 4 shows the temperature dependence of the ideality factor of the solar cells with various *p*-*a*-DLC:H thickness. The ideality factor for the tunneling process can be described by the following temperature dependent equation:[8]

$$n=\frac{E_{00}}{kT}\coth\left(\frac{E_{00}}{kT}\right), \tag{5}$$

where E_{00} is the characteristic tunneling energy, defined in Ref. 8. With increasing the *p*-*a*-DLC:H thickness, the *n* value increases more rapidly in the lower temperature region, as shown in Fig. 4. The solid curve represents the fitting result of Eq. (5) with $E_{00}=56$ meV to the experimental data of the

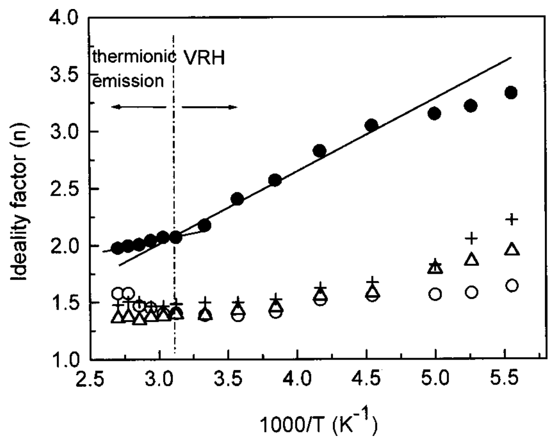

FIG. 4. Temperature dependence of the ideality factor (n) of the cells with p-a-DLC:H/50-Å-thick p-a-SiC:H. The thicknesses of the p-a-DLC:H layer are 0 Å (○), 5 Å (△), 15 Å (+), and 45 Å (●).

cell with a 45 Å-thick p-a-DLC:H/p-a-SiC:H. The increase of the n value at lower temperatures is known to originate from the contribution of the multistep-tunneling conduction to the diffusion process.[8] That is, at a lower temperature (<280 K) where carriers freeze out of the valence band, the hopping conduction of carriers begins to appear dominantly through the localized states of the p-a-DLC:H. Under illumination, photogenerated holes in the intrinsic layer experience the tunneling by the hopping conduction in the p-a-DLC:H layer. This is similar to hole transport in the case of the reverse saturation current at room temperature because the photocarriers are collected by the internal field under the short circuit condition, and the reverse saturation current is collected by the sum of the internal field and reverse bias.

In conclusion, we investigated the transport mechanisms in p-a-DLC:H of the solar cell by the temperature dependence of $J_0(T)$ and the ideality factor. For the cell with a 45 Å-thick p-a-DLC:H, the thermionic emission was dominant in the temperature range above 300 K and the tunneling process by the hopping mechanism was dominant below 300 K. The interfacial p-a-DLC:H between the SnO_2 and p-a-SiC:H was elucidated to lower the Schottky barrier against hole transmission at the junction of the SnO_2 and p-a-SiC:H. Moreover, the tunneling of photocarriers through the p-a-DLC:H is hindered and the series resistance effect appears severely with increasing the p-a-DLC:H. Therefore, it is concluded that an ultrathin ($\leqslant$15 Å) p-a-DLC:H is suitable for a hole emitter to enhance the performance of a-Si:H solar cells.

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