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\[ I_0 = B \{ \sigma_p v_{th} N_V \exp[-(E_T - E_V)/kT] \\
+ \sigma_n v_{th} N_C \exp[-(E_C - E_F)/kT] \} \]  \hspace{1cm} (4-7)

By comparing Eqs. (4-3) and (4-7) with the experimental data, several possibilities can be deduced. For the junction property using p c-Si with the lowest resistivity (sample 5), the value of \( \Delta E_{af} = 0.72 \) eV was obtained. This coincides with the activation energy \( \delta_2 \) (=\( E_C - E_F \)) of the dark conductivity of undoped a-Si:H. Therefore, considering the energy-band diagram shown in Fig. 4.4(b), the electron-capture rate is larger than the hole-emission rate, that is, the second term predominates in the right-hand side of Eq. (4-7). For samples 6-8, on the other hand, the obtained values of \( \Delta E_{af} \) were 0.80, 0.65, and 0.63 eV, respectively, which correlates with an increase in the substrate resistivity. As is clear from Fig. 3.10(b)-(d), the magnitude of \( E_T - E_V \) decreases with an increase in the substrate resistivity. This suggests that the hole emission dominates for these samples, namely, the first term in the right-hand side of Eq. (4-7) determines the magnitude of \( I_0 \). It is in progress that the transition from the electron-capture process to the hole-emission process is discussed in detail.

4-4. Reverse I-V Characteristics

The a-Si:H/c-Si heterojunctions can keep a small dark current even at higher reversed bias range, as shown in Figs. 4.1 and 4.2. From Eq. (4-1), the saturated value of the reverse current is expected to be \( I_0 \). However, the reverse current exceeds the value of \( I_0 \), indicating that the reverse current should be limited by another transport mechanism.

Figure 4.5 shows the reverse current as a function of \((V_B-V)^{1/2}\) for samples 5 and 6 with lower-resistivity p c-Si substrates, which is replotted from the data given in Fig. 4.2(a) and (b), respectively. Figure 4.6 shows the reverse current as a function of \((V_B-V)^{1/2}\) in the larger range of \(-5 \leq V \leq -0.5 \) V,
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Fig. 4.5. Reverse I-V characteristics of samples 5 and 6. The values of $V_B$ are 0.60 and 0.50 V for samples 5 and 6, respectively. The resistivities for samples 5 and 6 are 0.005-0.01 and 0.1-0.15 Ω cm, respectively.

Fig. 4.6. Reverse I-V characteristics of sample 21099. The value of $V_B$ is 0.35 V and $N_A$ is $1.0 \times 10^{16}$ cm$^{-3}$. 

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which is replotted from the data given in Fig. 4.1. When a generation current is taken into account in the depletion region, this current should be proportional to the width of the depletion region that varies with \((V_B-V)^{1/2}\). The data show a good linearity, indicating that their reverse currents should be limited by the generation process in the depletion region. This proportionality between reverse current and \((V_B-V)^{1/2}\) is held throughout the temperature range studied here. In sample 5, the depletion region exists only on the a-Si:H side because the p c-Si is heavily B-doped, indicating that its generation current is produced in the depletion region of a-Si:H under reverse bias conditions.

The reverse current is an increasing function of the p c-Si resistivity, as shown in Fig. 4.2. Because the width of the depletion region in c-Si increases with an increase of the p c-Si resistivity as shown in Fig. 3.10, the contribution of the generation current in p c-Si to the reverse current increases with an increase of the c-Si resistivity. Those suggest that the generation current per unit volume in the depletion region of c-Si is greater than that in the depletion region of a-Si:H. This may be because the bandgap (1.12 eV) of c-Si is narrower than that (about 1.7 eV) of a-Si:H.

4-5. Summary

The current-transport mechanism of the undoped a-Si:H/p c-Si heterojunctions has been discussed from their I-V characteristics and their temperature dependence. The main results are summarized as follows.

1. The forward current, described as \(\exp(-\Delta E_{af}/kT) \times \exp(AV)\), can be explained by a multistep-tunneling capture-emission (MTCE) model, where a hole in the valence band of p c-Si keeps flowing from one gap state to another in a-Si:H by the multistep-tunneling process until its tunneling rate becomes smaller than a rate either for hole releasing from the state to the valence band or for its recombination with an electron in the