also shown in Fig. 3.9, which is deviated from the straight line. This apparent invalidity of Eq. (3-11) simply originates from a thinner undoped a-Si:H layer (0.8 \mu m thick). The depletion layer spreads over the whole a-Si:H (i.e., \(W_2=L\)) when the reverse bias voltage exceeds some critical value, resulting in an upward break of the characteristic curve because much more fraction of reverse bias voltage is supported in p c-Si than that expected from Eq. (3-9). On other words, the slope of the \(W_2/V\) characteristics changes from \(2\varepsilon_{s1}\varepsilon_{s2}N_1/qN_A(N_A\varepsilon_{s1}N_1\varepsilon_{s2})\) to \(2\varepsilon_{s1}/qN_A\) as the reverse bias voltage increases from the critical value to higher reverse bias. Using the value of \(N_1\) obtained from sample 7, the critical bias voltage, at which \(W_2\) reaches to \(L\) (0.8 \mu m) for sample 3, was calculated as around -2 V, being in good agreement with the data in the figure.

The dependence of \(N_1\) on the p c-Si resistivity is studied. The undoped a-Si:H films of samples 5-8 were deposited simultaneously on four different p c-Si substrates. The capacitances of samples 5 and 6 (lower resistivities of p c-Si) were independent of the applied voltage, resulting from the formation of the wide depletion region only in the side of a-Si:H because \(N_A\) is much larger than \(N_1\). On the other hand, the value of \(N_1\) obtained from sample 7 with the p c-Si resistivity of 1-2 \(\Omega\) cm coincided with that of sample 8 with the resistivity of 5-10 \(\Omega\) cm. And also the undoped a-Si:H films of samples 9 and 10 were deposited simultaneously by the inductively-coupled rf glow discharge on two different p c-Si substrates. Both of \(N_1\) were quite similar, as shown in Table 3-1.

From the studies of the thickness- and resistivity-dependencies, the steady-state HMC method is considered to be reasonable for the present heterojunctions. From the resistivity-dependence, one had better select p c-Si with \(N_A\) which is close to the value of \(N_1\), indicating that several p c-Si substrates should be used in order to estimate \(N_1\) in the case that \(N_1\) is unknown at all.

3-2-3. Band discontinuity between a-Si:H and c-Si

Knowing band discontinuities at amorphous/crystalline
semiconductor heterojunctions is important in order to describe their electric properties as well as to design a heterojunction-bipolar transistor (HBT) with a wide-bandgap emitter.\textsuperscript{1}) As is clear from the energy-band diagram shown in Fig. 3.6, the energy difference between the conduction band in a-Si:H and the Fermi level at the interface is expressed as $qV_{B2}+\delta_2$ in the a-Si:H side and $\Delta E_C-qV_{B1}+E_{g1}-\delta_1$ in the c-Si side. Therefore, $\Delta E_C$ is expressed by

$$\Delta E_C = \delta_1 + \delta_2 - E_{g1} + qV_B . \quad (3-12)$$

On the other hand, $\Delta E_C$ is defined as

$$\Delta E_C = x_1 - x_2 . \quad (3-13)$$

Experimentally, the value of $\delta_1$ is estimated from $N_A$ as shown in Table 3-1 and the value of $\delta_2$ is the same as the activation energy of dark conductivity of a-Si:H. By substituting quantitative data on $\delta_1$, $\delta_2$, $x_1$, $E_{g1}$, and $V_B$ to Eqs. (3-12) and (3-13), the values of $\Delta E_C$ and $x_2$ are determined as

$$\Delta E_C = 0.20 \pm 0.07 \text{ eV}$$

and

$$x_2 = 3.85 \pm 0.07 \text{ eV} ,$$

using $E_{g1}=1.12 \text{ eV}$ and $x_1=4.05 \text{ eV}$.\textsuperscript{9}) Figure 3.10 shows the energy-band diagrams for the diodes (samples 5-8) with four different p c-Si resistivities, sketched on the basis of the above results.

3-3. Simulation of High-frequency C-V Characteristics

3-3-1. Modeling

Though only the undoped (i.e., slightly n-type) a-Si:H/p c-
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Fig. 3.10. Energy-band diagrams in interface regions for heterojunctions using p c-Si with different resistivities. Resistivities of p c-Si are (a) 0.005-0.01 Ω cm, (b) 0.1-0.15 Ω cm, (c) 1-2 Ω cm, and (d) 5-10 Ω cm.

Fig. 3.11. Schematic sketches of p c-Si/undoped a-Si heterojunction: (a) energy-band diagram, (b) energy variation for electron, and (c) space-charge density variation for dc reverse-bias voltage condition. Gap states indicated by hatched area of (a) are occupied by electrons.