the interface layer was taken into account, were similar to those in Fig. 3.12, although the lowest reverse bias, where the discrepancy from the straight line starts to occur, is higher than the reverse bias (about 0.7 V) calculated without the effect of the interface layer. Figure 3.15 shows the dependence of N_I and V_B on the charge ($Q_{SS}=N_S^* d_S$) of the interface layer for $g_{max}=3x10^{16}$ $cm^{-3}eV^{-1}$ and $N_A=10^{16}$ cm^{-3}. In the region of $N_S^* \leq 2x10^{17}$ cm^{-3} (i.e., the interface-state density Q_{SS} is less than 10^{11} cm^{-2}), the values of N_I and V_B are quite close to the values of N_I^* and V_B^*, respectively, then they increase rapidly with N_S^* in the case of $N_I^*=5.9x10^{15}$ cm^{-3}. These increases result from Q_{SS}. This critical value of Q_{SS} (or N_S^*) increases with an increase of N_I^*.

It is clear from the above results that if Q_{SS} is low, the values of N_I and V_B obtained by the steady-state HMC method represent the real midgap-state density and the real built-in potential, respectively.

3-4. Summary

The high-frequency (e.g., 100-kHz) C-V characteristics of undoped (i.e., slightly n-type) a-Si:H/p c-Si heterojunctions have been studied experimentally as well as theoretically. These heterojunctions have been found to form depletion regions in both sides of a-Si:H and c-Si by dc bias voltages, and energy-band diagrams for those heterojunctions with four different resistivities of p c-Si have been presented. Since the measuring frequency is much higher than the reciprocal of the dielectric relaxation time of the high-resistivity undoped a-Si:H, the capacitance in the a-Si:H side is determined by the thickness of the a-Si:H film. That is why the measuring capacitance at the high frequency becomes a series of this capacitance in a-Si:H and the other capacitance which is determined by the width of the depletion region in c-Si. Moreover, the trapping/detrapping processes cannot respond to the high-frequency ac voltage, which easily enables us to analyze the C-V characteristics. The main results are summarized as follows:

(1) The high-frequency C-V characteristics of the heterojunctions with high-resistivity a-Si:H have been successfully analyzed, from which it has been made clear that the abrupt heterojunction model is valid for a-Si:H/c-Si heterojunctions.

(2) A method for estimating the midgap-state density (N_I) of undoped a-Si:H has been developed, which is called a steady-state heterojunction-monitored capacitance (HMC) method. Those densities of the highly resistive films have been difficult to be estimated from the studies of Schottky barrier junctions and homogeneous p-n junctions.

(3) The conduction-band discontinuity between a-Si:H and c-Si has been estimated as 0.20 ± 0.07 eV, from which the electron affinity of a-Si:H is found to be 3.85 ± 0.07 eV.

(4) A model for simulating high-frequency C-V characteristics of those heterojunctions has been developed for the first time, and the physical background of the space-charge density (N_I) of the amorphous film, which is obtained from the steady-state HMC method, has been discussed.

(5) From the simulation of their high-frequency C-V characteristics, in the reasonable case that their interface-state density is less than 10^{11} cm^{-2}, the values of N_I and V_B obtained by the steady-state HMC method are found to represent the midgap-state density of the amorphous film and the built-in potential of the heterojunction, respectively.