and conduction-band discontinuity (ΔE_C) between a-Si:H and c-Si are discussed. Moreover, in order to make the above discussion clearer, a model for simulating high-frequency C-V characteristics of highly resistive amorphous/lowly resistive crystalline semiconductor heterojunctions has been developed, where the high frequency indicates a frequency higher than f_{de}.

3-2. Experimental High-frequency C-V Characteristics

3-2-1. C-V characteristics

In the case of undoped a-Si:H the thermal emission rate of electrons from a gap state to the conduction band is usually much lower than the capture rate of electrons from the conduction band into the gap state, indicating that the capacitance should be measured from a higher to a lower reverse bias. In order to get the steady-state condition, moreover, the voltage sweep rate (dV/dt) should be small, for example, the C-V characteristics in this study were measured at dV/dt smaller than 0.004 V/s, and the heterojunction at the highest reverse bias (starting bias for the C-V measurements) was kept for a few minutes. Figure 3.3 shows typical high-frequency C-V characteristics of an undoped a-Si:H/p c-Si heterojunction with the acceptor density (N_A) in p c-Si of 1.0×10^{16} cm^{-3}. When p c-Si is replaced by p^+ c-Si, having the resistivity of $\leqq 0.01$ Ω cm, the capacitance was found to be independent of the applied voltage. The value of this capacitance is found to be determined by the film thickness of the undoped a-Si:H layer, and it is the same as that of the saturated capacitance (C_2) in the positive bias region in Fig. 3.3, indicating that the dc applied bias forms the wide depletion region in a-Si:H but the negligible depletion region in p^+ c-Si. This suggests that the capacitance in Fig. 3.3 is a series of the capacitance determined by the width (W_1) of the depletion region in c-Si and the capacitance determined by the thickness (L) of the a-Si:H film.

In order to explain the high-frequency C-V characteristics, two kinds of models have been proposed;

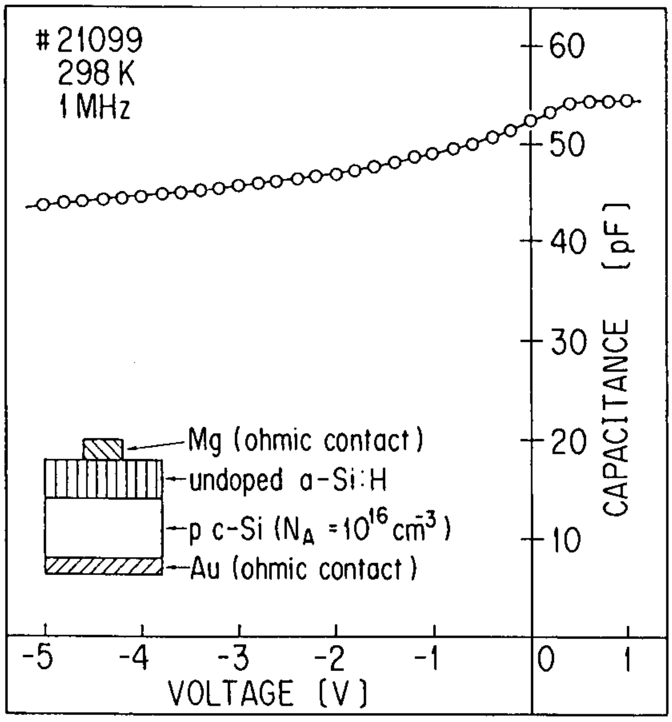

Fig.3.3. C-V characteristics of undoped a-Si:H/p c-Si heterojunction.

CHAPTER III C-V CHARACTERISTICS

1. a metal-oxide-semiconductor (MOS)-type model, where a-Si:H is considered to behave as an oxide layer (i.e., insulator);[3-5]
2. a p-n junction-type model.[6,7]

In the MOS-type analysis, the electric field produced by the dc applied bias should be constant over a-Si:H. Furthermore, the quasi-Fermi level for electrons is assumed to coincide with the quasi-Fermi level for holes in the depletion region, which means that at any applied bias the Fermi level can be defined in the depletion region. In the p-n junction-type analysis, on the other hand, the electric field produced by the dc applied bias should not be constant in a-Si:H at all and exists only in the depletion region. Moreover, when the dc bias is applied across the junction, the quasi-Fermi level for electrons is separated from the quasi-Fermi level for holes in the depletion region. As is clear from Fig. 2.3, the undoped a-Si:H/p^+ c-Si heterojunction, where the depletion region formed by the dc bias is negligible in p^+ c-Si, exhibits a good rectifying property, suggesting that the current should be controlled by the change of the depletion width in a-Si:H. In the case of the undoped a-Si:H/p c-Si heterojunctions which will be investigated here, therefore, the C-V characteristics should be analyzed by using the p-n junction-type analysis. Another evidence is also presented as follows.

The frequency dependence of the C-V characteristics for the a-Si:H/p c-Si heterojunction at 298 K is shown in Fig. 3.4. The frequency of 1 kHz remains higher than the reciprocal of the dielectric relaxation time given by $1/2\pi\varepsilon_{s2}\rho_2$ (about 160 Hz), where ε_{s2} is the semiconductor permittivity of undoped a-Si:H and ρ_2 is the resistivity of undoped a-Si:H. The C-V characteristics measured at 100 Hz were much different from those given in Fig. 3.4. The saturated capacitance (C_2) observed at a high forward bias for 1-MHz curve did not appear at the frequency lower than 100 Hz, because the capacitance in a-Si:H is no longer determined by the thickness of the a-Si:H film. On other words, the capacitance in principle approaches a series of the capacitance determined by the depletion width (W_1) in c-Si and

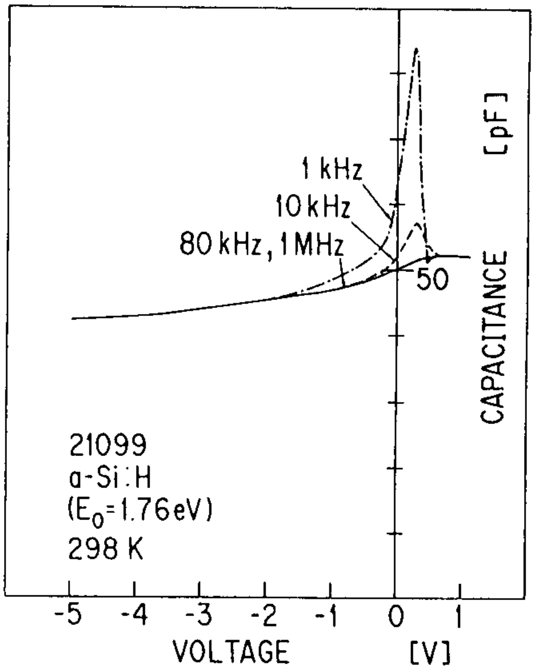

Fig.3.4. Set of four C-V characteristics at 298 K corresponding to different measuring frequencies for undoped a-Si:H/p c-Si (N_A=1.0x10^{16} cm^{-3}) heterojunction.

the capacitance determined by the depletion width (W_2) in a-Si:H instead of the thickness (L) of a-Si:H, as the measuring frequency decreases from 160 Hz, as long as the capacitance due to the trapping/detrapping processes is neglected. That is why the p-n junction analysis should be applied to discussing those C-V characteristics as will be described in the next section. In the figure, the capacitance measured at $V \leqq -2$ V is independent of the frequency, while the capacitance at $V \geqq -2$ V depends on the frequency, indicating that the information obtained in the range of $V \leqq -2$ V is unaffected by capacitances (e.g., diffusion capacitance) which results from the current flow across the heterojunction due to an ac voltage.

The low-frequency (<160-Hz) C-V characteristics are affected not only by the dielectric relaxation process but also by the trapping/detrapping process of electrons and holes between gap states and the extended states, indicating that the midgap-state density obtained from those low-frequency C-V characteristics depends on the measuring frequency. Furthermore, the simulation of their low-frequency C-V characteristics has been so difficult that the physical background of the apparent midgap-state density could not be understood clearly, as is similar to the case of Schottky barrier junctions. Although the zero-frequency C-V characteristics have been simulated because it is not necessary to consider the dielectric relaxation process and the trapping/detrapping process, those cannot experimentally be measured in fact. Since the high frequency enables us to neglect the dielectric relaxation process as well as the trapping/detrapping process, the simulation of the high-frequency C-V characteristics must be possible. Therefore, the C-V characteristics under a frequency much higher than 160 Hz have been measured and discussed in this chapter.

3-2-2. Steady-state heterojunction-monitored capacitance method

In order to understand the above results more clearly, a systematic study of undoped a-Si:H/p c-Si heterojunctions has been performed. Undoped a-Si:H films were deposited by the rf glow-discharge decomposition of pure SiH_4 on four kinds of p c-Si