CHAPTER III CAPACITANCE-VOLTAGE CHARACTERISTICS OF UNDOPED a-Si:H/p c-Si HETEROJUNCTIONS

3-1. Introduction

Hydrogenated amorphous silicon (a-Si:H) has been a highly important material for device applications. In order to take advantage of both the good properties of a-Si:H and crystalline silicon (c-Si), electric properties of a-Si:H/c-Si heterojunctions have been intensively studied.[1,2] Moreover, the study of these heterojunctions helps to obtain a midgap-state (i.e., space-charge) density (N_I) of undoped a-Si:H, with which the electronic properties of a-Si:H-based devices are critically linked.

In the case of lowly resistive semiconductor (e.g., c-Si and P-doped a-Si:H), it is easy to estimate the value of its space-charge density which determines the depletion width in it using Schottky barrier junctions and p-n junctions. In the case of highly resistive semiconductor (e.g., undoped a-Si:H), however, it is quite difficult to do using those junctions. Figure 3.1 shows the schematic energy-band diagram and the equivalent circuit of a Schottky barrier junction, where C_D is the capacitance determined by the depletion width (W_2), which is expressed as $C_D = \varepsilon_{s2}/W_2$, C_g is the capacitance due to the trapping/detrapping processes of electrons between gap states and the conduction band, C_B is the capacitance determined by the width in the bulk region [i.e., $C_B = \varepsilon_{s2}/(L-W_2)$], and G_B is the conductance in the bulk region. Here, L is the thickness of undoped a-Si:H. The influence of admittance in the bulk region on the measuring capacitance (C) changes with the measuring frequency. The frequency, which corresponds to a dielectric relaxation time in the film, is considered;

$$f_{de} = G_B/2\pi C_B$$

$$= 1/2\pi \varepsilon_{s2}\rho_2 \quad ,$$

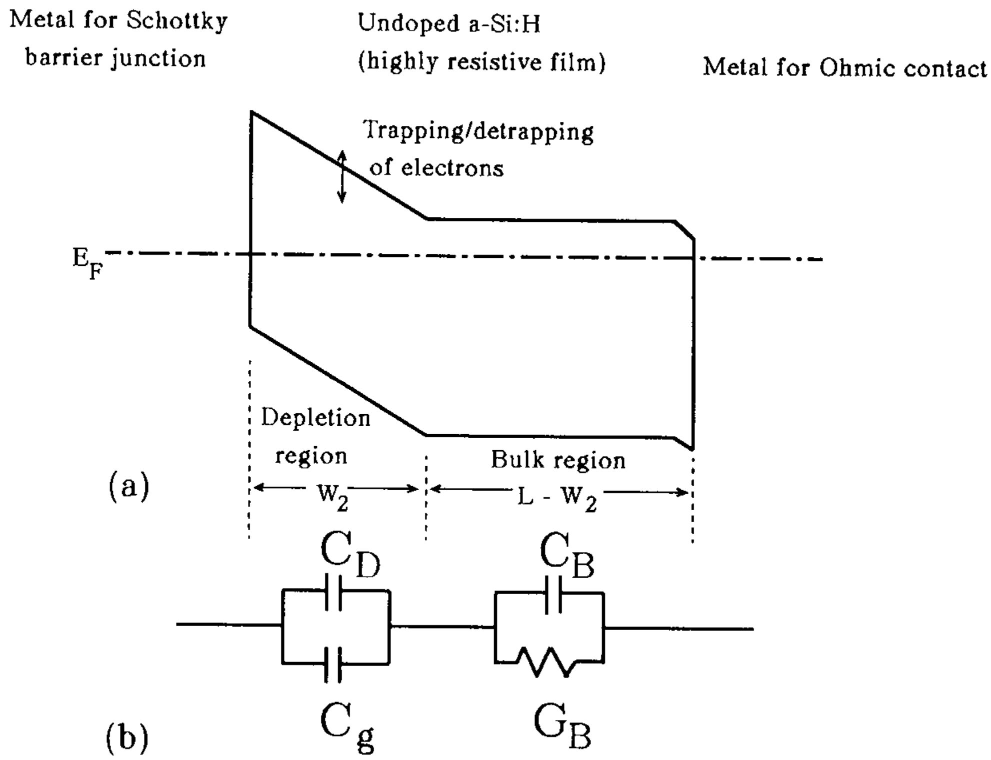

Fig.3.1. Schematic sketches of (a) energy-band diagram in Schottky barrier junction and (b) equivalent circuit.

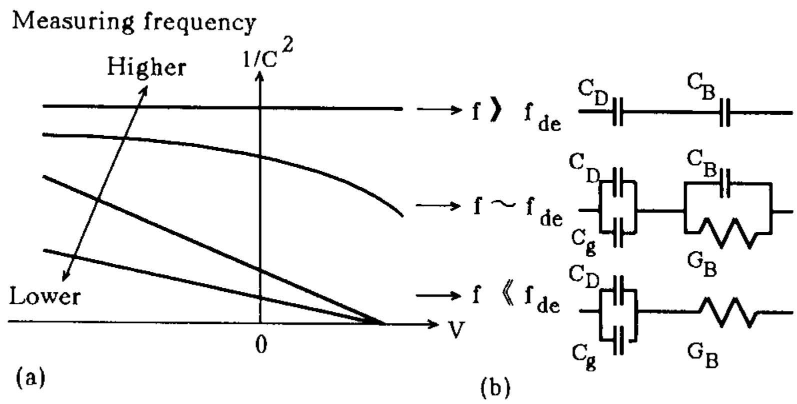

Fig.3.2. Frequency dependencies of (a) $1/C^2$-V characteristics and (b) equivalent circuits.

where ε_{s2} and ρ_2 are the semiconductor permittivity and the resistivity of highly resistive amorphous semiconductor, respectively, and $\varepsilon_{s2}\rho_2$ is referred to as a dielectric relaxation time. In the case of undoped a-Si:H ($\varepsilon_{s2} \sim 12\varepsilon_0$, and $\rho_2 \sim 10^9$ Ω cm),

$$f_{de} \sim 160 \text{ Hz}$$

and

$$\varepsilon_{s2}\rho_2 \sim 10^{-3} \text{ s} \quad .$$

Figure 3.2 shows the schematic $1/C^2$-V characteristics and the equivalent circuits corresponding to different measuring frequencies. At a frequency much higher than 160 Hz, C becomes constant and is given by the thickness of the undoped a-Si:H film as $C=\varepsilon_{s2}/L$. At a frequency much lower than 160 Hz, however, C becomes the value of C_D+C_g and $1/C^2$ is empirically proportional to V. The space-charge density can be estimated from the reciprocal of this slope, but it is strongly dependent on the measuring frequency because of frequency dependence of C_g. In order to estimate N_I which determines the depletion width, the value of C_D should be measured because of $C_D=\varepsilon_{s2}/W_2$.

The main discussion in this chapter is derived from the study of undoped a-Si:H/p-type crystalline silicon (p c-Si) heterojunctions. As is clear from Chapter II, a Mg/undoped a-Si:H/p c-Si diode enables us to investigate the undoped (i.e., slightly n-type) a-Si:H/p c-Si heterojunction. These heterojunctions, moreover, are found to behave like a p-n junction. On other words, the depletion regions are formed in both sides of a-Si:H and c-Si, and vary with a dc applied voltage, resulting from the evidences that the current in the diode is limited by the undoped a-Si:H/p c-Si heterojunction as well as that the heterojunction exhibits a good rectifying property.

The high-frequency C-V characteristics of those heterojunctions have experimentally been studied, from which N_I

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 $1.0\mathrm{x}10^{16}$ cm^{-3}. When p c-Si is replaced by p^+ c-Si, having the resistivity of ≤ 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;