below the Fermi level in highly resistive amorphous films can be determined from the experimental results involving measurements of transient capacitance as well as its temperature-dependence of those heterojunctions.

## 5-2. Transient Capacitance

Figure 5.1 shows the change in the capacitance after a reverse-bias voltage (-4 V) is applied to an undoped a-Si:H/p c-Si ($N_A$=1.0x$10^{16}$ $cm^{-3}$) heterojunction which was under the zero-bias condition for a certain time. In almost of the whole a-Si:H, the gap states between $E_F$ and $E_{0B}$ are full of electrons under the zero-bias condition. After applying the reverse-bias voltage, the electrons trapped at the gap states between $E_F$ and $E_{0B}$ are going to be re-emitted to the conduction band, which results in the change of the positive space-charge density in the depletion region of undoped a-Si:H. Because a-Si:H possesses deep gap states whose emission rates are small, the capacitance gradually decreases with time (t). Since the steady-state HMC method has made it possible to get the midgap-state density, this transient HMC must include information on the g(E) of the midgap states. From the transient behavior of the capacitance, the g(E) in undoped a-Si:H can be determined as discussed in the following sections. This method is a powerful technique for determining the g(E) below the Fermi level in undoped a-Si:H because it has been difficult to obtain the g(E) in such a highly resistive semiconductor by the conventional transient capacitance methods, such as deep-level transient spectroscopy (DLTS)[1] and isothermal capacitance transient spectroscopy (ICTS)[2] using Schottky barrier diodes and homogeneous p-n diodes, as mentioned in Chapter I .

## 5-3. Theory of Transient HMC Method

In order to estimate the g(E) below the Fermi level, the

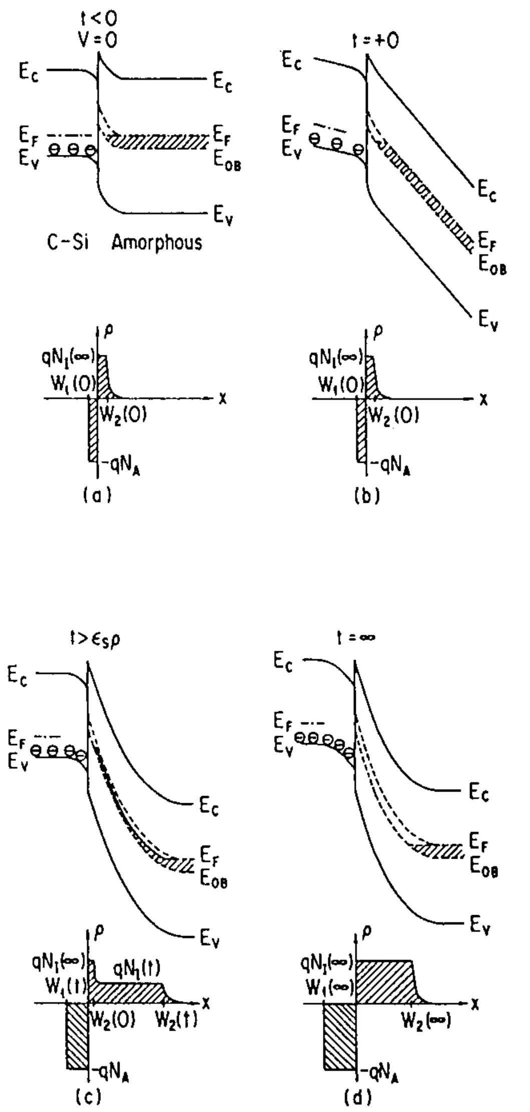


**Fig.5.2.** Schematic representation of energy-band diagram and space-charge density of heterojunction at four different times: (a) t<0, (b) t=+0 , (c) $t>\varepsilon_S\rho$ , and (d) $t=\infty$. In energy-band diagrams, gap states as indicated by hatched areas are occupied by electrons, so are neutral. In the depletion region, therefore, empty gap states between $E_F$ and $E_{OB}$ behave as positively charged states. Gap states below $E_{OB}$ are always occupied by electrons. The symbol of ⊖ represents a negatively charged acceptor.

transient HMC is considered after a reverse-bias voltage ($V_R$) is applied to the sample for a certain period of time. The zero-bias condition is kept for t<0 s in order to fill electrons at gap states below the Fermi level, as shown in Fig. 5.2(a). At t=+0 s, the voltage $V_R$ is applied across the whole regions of a-Si:H and c-Si as shown in Fig. 5.2(b). Electrons trapped at shallower states are thermally emitted into the conduction band. After the applied bias has been on the dielectric relaxation time of the amorphous film, the space charge in the vicinity of the heterojunction will redistribute itself in response to the applied potential [Fig. 5.2(c)]. Here, the dielectric relaxation time of c-Si is much shorter than that of the amorphous film.

The HMC data after the dielectric relaxation time can be analyzed using Eq. (3-11), where $W_1$ and $N_I$ are a function of time (t), thus,

$$W_1^2(t) = 2\varepsilon_{s1}\varepsilon_{s2}N_I(t)(V_B - V_R)/qN_A[N_I(t)\varepsilon_{s2} + N_A\varepsilon_{s1}]. \quad (5\text{-}1)$$

Since

$$V_1(t) = qN_AW_1^2(t)/2\varepsilon_{s1} \quad , \quad (5\text{-}2)$$

Eq. (5-1) can be written as

$$V_1(t)[N_I(t)\varepsilon_{s2} + N_A\varepsilon_{s1}] = \varepsilon_{s2}N_I(t)(V_B - V_R) \quad . \quad (5\text{-}3)$$

By solving $N_I(t)$ from Eq. (5-3), we obtain

$$N_I(t) = \varepsilon_{s1}V_1(t)N_A/\varepsilon_{s2}[V_B - V_R - V_1(t)] \quad , \quad (5\text{-}4)$$

where $W_1(t)$ is the depletion width in c-Si at time t and $V_1(t)$ is the voltage at t across the depletion region of c-Si. From Eq. (3-10), on the other hand, we can also obtain experimentally

$$W_1(t) = \varepsilon_{s1}[1/C(t) - 1/C_2] \quad , \quad (5\text{-}5)$$

where C(t) is the measured capacitance (HMC) at t, as shown in

Fig. 5.1. To make the above analysis feasible, the absolute value of $V_R$ must be high enough for $N_I(t)W_2(t)$ to become much larger than $N_I(\infty)W_2(0)$, indicating that the average value of $N_I$ over the depletion region at t becomes close to $N_I(t)$. This condition also suggests that its interface states do not affect the measurement of HMC.

The function H(t) is defined as

$$H(t) \equiv td[\Delta N_I(t)]/dt \quad , \qquad (5\text{-}6)$$

with

$$\Delta N_I(t) \equiv N_I(t) - N_I(\infty) \quad . \qquad (5\text{-}7)$$

Since $N_I(\infty)$, which represents $N_I$ at $t=\infty$ s, is constant, Eq. (5-6) can be rewritten as

$$H(t) = tdN_I(t)/dt \quad . \qquad (5\text{-}8)$$

Therefore, the HMC signal of H(t) is experimentally obtained from Eqs. (5-2), (5-4), (5-5) and (5-8).

On the other hand, the signal of H(t) is theoretically considered. The value of $\Delta N_I(t)$ is determined by the change in the electron occupation of the g(E), thus:(See Appendix)

$$\Delta N_I(t) = -\int_{E_V}^{E_C}[f(E) - F_\infty(E)]g(E)\exp\{-[e_n(E) + e_p(E)]t\}dE, \qquad (5\text{-}9)$$

where $E_C$ and $E_V$ are the conduction-band edge and valence-band edge, respectively, f(E) is the Fermi-Dirac distribution function which coincides with the occupation function at t=0 s, $F_\infty(E)$ is the occupation function at $t=\infty$ s, and $e_n(E)$ and $e_p(E)$ are thermal emission rates of electrons and holes, respectively. The function f(E) is expressed as

$$f(E) = 1/\{1 + \exp[(E - E_F)/kT]\} \quad , \qquad (5\text{-}10)$$

and $F_\infty(E)$ is given by the thermal-emission process:(See Appendix)

$$F_\infty(E) = e_p(E)/[e_n(E) + e_p(E)] \quad . \tag{5-11}$$

The values of $e_n(E)$ and $e_p(E)$ are described as

$$e_n(E) = \nu_n \exp[(E - E_C)/kT] \tag{5-12}$$

and

$$e_p(E) = \nu_p \exp[(E_V - E)/kT] \quad . \tag{5-13}$$

Then from Eqs. (5-6) and (5-9), we obtain

$$H(t) = \int_{E_V}^{E_C} [f(E) - F_\infty(E)]g(E)[e_n(E) + e_p(E)]t \times \exp\{-[e_n(E) + e_p(E)]t\}dE \quad . \tag{5-14}$$

The determination of g(E), by which H(t) of Eq. (5-14) can be obtained to fit the measured H(t) using Eqs. (5-10)-(5-13), is described in the next section.

In the case that $e_n(E)$ is much larger than $e_p(E)$, on the other hand, the following relation between g(E) and H(t) is obtained. Equation (5-14) can be rewritten as

$$H(t) = \int_{E_V}^{E_C} [f(E) - F_\infty(E)]g(E)D(E,t)dE \quad , \tag{5-15}$$

where

$$D(E,t) = e_n(E)t \exp[-e_n(E)t] \quad . \tag{5-16}$$

The function D(E,t) is maximum at $e_n(E)t=1$. If this function is assumed to be a delta function, the following relation could be obtained approximately:

$$H(t_m) \fallingdotseq [f(E_m) - F_\infty(E_m)]g(E_m) \int_{E_V}^{E_C} D(E,t_m)dE$$

$$\fallingdotseq [f(E_m) - F_\infty(E_m)]g(E_m) \int_{0}^{\infty} D(E,t_m)dE$$

$$= [f(E_m) - F_\infty(E_m)]g(E_m)kT \quad , \qquad (5\text{-}17)$$

where $E_m$ is the energy at which D(E,t) has a maximum value when

$$e_n(E_m)t_m = 1 \quad . \qquad (5\text{-}18)$$

Therefore, the relation between $E_m$ and $t_m$ is derived from Eqs. (5-12) and (5-18):

$$E_C - E_m = kT\ln(\nu_n t_m) \quad . \qquad (5\text{-}19)$$

In a more general form, this equation can be expressed as

$$E_C - E(t) = kT\ln(\nu_n t) \quad . \qquad (5\text{-}20)$$

Under the conditions that $e_n(E)$ is much higher than $e_p(E)$ [i.e., $F_\infty(E)=0$] as well as that f(E) is close to unity for the gap states between $E_F$ and $E_{OB}$, the relation between H(t) and g(E) is generally obtained from Eq. (5-17) as

$$g(E) = H(t)/kT \quad . \qquad (5\text{-}21)$$

Therefore, the g(E) around the middle of the energies between $E_F$ and $E_{OB}$ can be easily estimated from the measured H(t) using Eqs. (5-20) and (5-21).

## 5-4. Transient HMC Measurements

Undoped a-Si:H films were deposited by the rf glow-discharge decomposition of pure $SiH_4$, and undoped a-$Si_{1-x}Ge_x$:H films were prepared by the rf glow-discharge decomposition of