to Al, even for n^+ a-Si:H which is usually introduced into a-Si:H devices as an intermediate layer between Al and undoped a-Si:H for getting Ohmic contacts.

In order to check the stability of the Mg/a-Si:H contact, a thermal annealing experiment at 374 K under N_2 atmosphere for 6 hours was performed. The I-V characteristics of the specimens showed no change before and after the thermal annealing.

On discussing the C-V and I-V characteristics of Mg/undoped a-Si:H/p c-Si diodes in Chapters III and IV, it is worthy of note that a dc applied voltage can form the depletion regions in not only p c-Si but also undoped a-Si:H of undoped a-Si:H/p c-Si heterojunctions, which is quite different from the case of chalcogenide/c-Si heterojunctions[5)] and amorphous germanium/crystalline germanium heterojunctions.[6)] Its reason is as follows. Since the contacts between metal(Pt,Au,Al) and undoped a-Si:H exhibit rectifying properties which originate from a Schottky barrier junction, the depletion region must be formed in the a-Si:H. Its another evidence was reported that at low frequency the diodes with those metal/a-Si:H contacts showed the C-V characteristics originating from the Schottky barrier junctions.[7)] Therefore, the quality of these undoped a-Si:H is good enough to form the depletion region in a-Si:H.

2-3. Contact Properties for B-doped a-Si:H

Junction properties of metal(Au,Mg)/B-doped a-Si:H/c-Si(n^+,p^+) structures as a function of B-doping level are studied, and the conduction type of each B-doped specimen in terms of carrier concentration is discussed. Crystalline Si wafers were soaked in a solution of HF to remove SiO_2 on c-Si, then rinsed in distilled water. B-doped as well as undoped a-Si:H films, ~ 1.5 μm in thickness, were deposited on both n^+ and p^+ c-Si heated to 300 ℃ by means of the rf glow-discharge decomposition of B_2H_6/SiH_4 gas mixtures; the B_2H_6-to-silane ratios were between 0 and 1.1×10^{-2}. A flow rate of 5 sccm, a gas pressure of 50 mTorr, and an rf power of 5 W were maintained during the deposition.

The dark conductivity of a-Si:H deposited in this way was measured in a coplanar electrode geometry on Corning 7059 glass substrate, and the lowest dark conductivity was around 10^{-12} S/cm at $B_2H_6/SiH_4 \sim 10^{-4}$. After depositing a-Si:H films, Au and Mg patterns were evaporated onto the virginal surface of each a-Si:H film to produce four different types of diodes; type-1(Au/a-Si:H/n^+ c-Si), type-2(Au/a-Si:H/p^+ c-Si), type-3(Mg/a-Si:H/n^+ c-Si), and type-4(Mg/a-Si:H/p^+ c-Si). The I-V measurements have been performed for these diodes at room temperature. In these diodes the depth profile of B concentration in the a-Si:H layer is found to be flat by secondary ion mass spectroscopy (SIMS). That is why c-Si is used as a substrate instead of heavily P- or B-doped a-Si:H, thereby avoiding "cross contamination" of the two a-Si:H layers.

Figure 2.5 shows the I-V characteristics of diodes (types 1-4) with the a-Si:H films deposited at five different doping levels;(a) B_2H_6/SiH_4=0, (b) 3.0×10^{-6}, (c) 1.5×10^{-5}, (d) 2.7×10^{-3}, and (e) 8.0×10^{-3}.

For the case of undoped a-Si:H, shown in Fig. 2.5(a), the type-3 diode shows Ohmic behavior and the current is limited by the resistance of the a-Si:H film, which means that the junctions of Mg/a-Si:H and n^+ c-Si/a-Si:H are Ohmic. The currents of type-2 and type-4 diodes, for a positive bias on both metals, are of the same order of magnitude, indicating that those currents are limited by the reverse-biased p^+ c-Si/a-Si:H junction in both diodes. Likewise, the similar I-V characteristics of type-1 and type-2 diodes for a negative bias on the metal(Au) imply that the currents are limited by the reverse-biased Au/a-Si:H junction. The properties of the junctions involved in each diode for B_2H_6/SiH_4=0 can then be classified qualitatively into "R" (rectifying) or "O" (Ohmic), and can be summarized in the first column of Table 2-1.

When diodes of B-doped a-Si:H with B_2H_6/SiH_4 ratio of 1.5×10^{-5} shown in Fig. 2.5(c) are compared with the diodes of undoped a-Si:H shown in Fig. 2.5(a), the type-2 diode in Fig. 2.5(c) shows the behavior similar to the type-3 diode in Fig. 2.5(a), indicating that the junctions of Au/a-Si:H and p^+ c-Si/a-

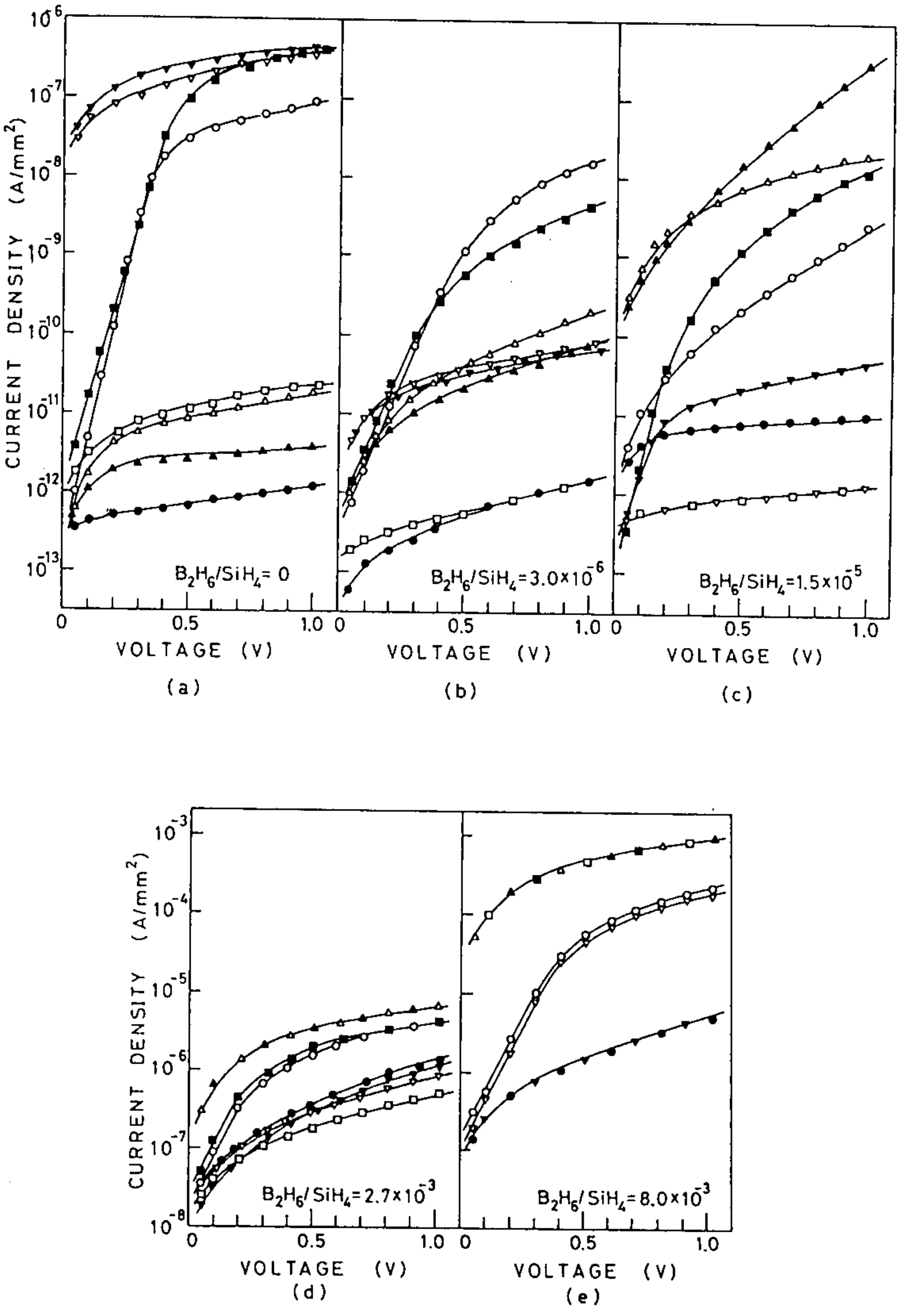

Fig. 2.5. I-V characteristics of four different types of diodes: ○,●, type-1 (Au/a-Si:H/n$^+$ c-Si); △,▲, type-2(Au/a-Si:H/p$^+$ c-Si); ▽,▼, type-3(Mg/a-Si:H/n$^+$ c-Si); and □,■, type-4(Mg/a-Si/p$^+$ c-Si). B_2H_6/SiH_4 ratios are (a) 0, (b) 3.0x10^{-6}, (c) 1.5x10^{-5}, (d) 2.7x10^{-3}, and (e) 8.0x10^{-3}. Open and solid marks represent data points for a positive bias and a negative bias voltage on metal, respectively.

TABLE 2-1. Properties of metal/semiconductor junctions and heterojunctions with various B-doped a-Si:H.

B_2H_6/SiH_4	Au/a-Si:H	p^+c-Si/a-Si:H	Mg/a-Si:H	n^+c-Si/a-Si:H	Conduction type[b]
0	R	R	O	O	n
7.0×10^{-7} 1.5×10^{-6} 3.0×10^{-6}	R	R	R	R	intrinsic
1.5×10^{-5} 2.7×10^{-3}	O	O	R	R	p
4.0×10^{-3} 8.0×10^{-3} 1.1×10^{-2}	O	O	O	R	p

[a] R:rectifying property, O:Ohmic property.
[b] Judging from junction properties.

Si:H are Ohmic for $B_2H_6/SiH_4=1.5x10^{-5}$. The currents of type-3 and type-4 diodes, for a positive bias on Mg, are of the same order of magnitude, supporting that those currents are limited by the reverse-biased Mg/a-Si:H junction in both diodes. Likewise, the similar I-V characteristics of type-1 and type-3 diodes for a negative bias on both metals imply that the currents are limited by the reverse-biased n^+ c-Si/a-Si:H junction. The behavior of the diodes with $B_2H_6/SiH_4=2.7x10^{-3}$, shown in Fig. 2.5(d), is similar to that with $B_2H_6/SiH_4=1.5x10^{-5}$. Therefore, the properties of the junctions involved in each diodes for the gas ratios of $1.5x10^{-5}$ and $2.7x10^{-3}$ can be summarized in the third column of Table 2-1.

Diodes of B-doped a-Si:H with B_2H_6/SiH_4 ratios of $4.0x10^{-3}$, $8.0x10^{-3}$, and $1.1x10^{-2}$ exhibit similar characteristics, as shown in Fig. 2.5(e). The currents of type-2 and type-4, which is quite different from those shown in Fig 2.5(c) and (d), are of the same order of the magnitude, indicating that the Mg/a-Si:H junction changes from rectifying into Ohmic when the B_2H_6/SiH_4 ratio increases from $2.7x10^{-3}$ to $4.0x10^{-3}$. On the other hand, the behavior of type-1 and type-3 results from that of the n^+ c-Si/a-Si:H junction. Then the properties of those junctions are classified, as shown in the fourth column of Table 2-1.

Diodes of B-doped a-Si:H with the gas ratios of $7.0x10^{-7}$, $1.5x10^{-6}$, and $3.0x10^{-6}$ exhibit similar characteristics, as shown in Fig. 2.5(b). The forward-biased currents of type-1 and type-4 diodes at higher voltages are limited by the resistance of the B-doped a-Si:H films. Since the currents of type-2 and type-3 diodes are substantially lower than the forward-biased currents of type-1 and type-4 diodes at higher voltages, it is reasonable to consider type-2 and type-3 diodes as back-to-back diodes. Then all junctions here are rectifying, as seen in the second column of Table 2-1.

The above results can be discussed in more detail using energy-band diagrams for the diodes of types 1-4 shown in Fig. 2.2. The energy-band diagrams were obtained on the basis of undoped a-Si:H films, as described in Section 2-2. But the essential features should be similar qualitatively for the diodes of B-doped a-Si:H. Since the junction properties of undoped a-Si:H are similar to those of P-doped a-Si:H as described in Section 2-2, the conduction type of undoped a-Si:H is n-type, i.e., the majority carriers in undoped a-Si:H are electrons. Therefore, junctions of Au/a-Si:H and p^+ c-Si/a-Si:H behave as a rectifying contact and agree with the experimental results summarized in Table 2-1.

For $B_2H_6/SiH_4 \geqq 1.5 \times 10^{-5}$, on the other hand, junctions of Mg/B-doped a-Si:H and n^+ c-Si/B-doped a-Si:H exhibit rectification, indicating that the conduction type of those B-doped a-Si:H in the above doping range is p-type, i.e., the majority carriers are holes. The junction of Mg/B-doped a-Si:H switches from rectifying to Ohmic when B_2H_6/SiH_4 exceeds 4.0×10^{-3}, which is due to tunneling of holes through the very thin Schottky barrier which results from the heavy doping of B.

In B-doped a-Si:H for doping ratios between 7.0×10^{-7} and 3.0×10^{-6}, all junctions exhibit rectification which means that both electrons and holes probably affect the junction properties; the concentration (p) of holes is nearly equal to that (n) of electrons.

From junction properties, the conduction type of a-Si:H deposited at $B_2H_6/SiH_4 \geqq 1.5 \times 10^{-5}$ is found to be p-type, while the minimum conductivity occurred at $B_2H_6/SiH_4 \sim 10^{-4}$, similar to the case of Spear and LeComber.[8] The conductivity is given by $q(\mu_p p + \mu_n n)$, where μ_p and μ_n are the drift mobilities of holes and electrons, respectively, and q the magnitude of electronic charge. Although p exceeds n at $B_2H_6/SiH_4 = 1.5 \times 10^{-5}$, $\mu_p p$ is still smaller than $\mu_n n$ because μ_p is much smaller than μ_n.[9-11] Therefore, the value of $\mu_p p$ is close to that of $\mu_n n$ at $B_2H_6/SiH_4 \sim 10^{-4}$.

Although it is general to determine the conduction type (p- or n-type) of semiconductor by means of Hall measurements, it is quite difficult to do in the case of a-Si:H because its low conductivity makes a Hall voltage immeasurably small. Spear and LeComber[8] have reported on the basis of the activation energy of film conductivity that a transition from n- to p-type conduction in a-Si:H occurs at $B_2H_6/SiH_4 \sim 10^{-4}$ since the activation energy shows the maximum at that doping ratio. In contrast, in the present work which is based on the junction properties we have successfully characterized B-doped a-Si:H into three categories of conduction type in terms of "dominant" carrier concentration; n-type for $B_2H_6/SiH_4<10^{-7}$, intrinsic for $B_2H_6/SiH_4\sim 10^{-6}$, and p-type for $B_2H_6/SiH_4>10^{-5}$.

On discussing the C-V characteristics of undoped a-Si:H/p c-Si heterojunctions, it is noteworthy that near the interface between undoped a-Si:H and p c-Si the energy band of undoped a-Si:H shows an upward bending, while the energy band of p c-Si shows a downward bending. This is because the conduction type of undoped a-Si:H is found to be n-type.

2-4. Summary

(1) The electrical properties of undoped a-Si:H/p c-Si heterojunctions can be investigated in Mg/a-Si:H/p c-Si diodes, because the Mg/undoped a-Si:H contacts are found to be Ohmic.

(2) In the undoped a-Si:H/p c-Si heterojunctions, the depletion regions are formed in both sides of a-Si:H and p c-Si, and these heterojunctions behave like a p-n junction because the conduction type of undoped a-Si:H is n-type.

(3) P-doped and undoped a-Si:H films make a rectifying contact with Au, Pt, Al, and p^+ c-Si, but those form an Ohmic contact with Mg and n^+ c-Si, indicating that majority carriers in those films are electrons.

(4) B-doped a-Si:H films, which are deposited in the range of $7x10^{-7}\leq B_2H_6/SiH_4\leq 3x10^{-6}$, form a rectifying contact with all of the metals(Au,Mg) and c-Si(n^+,p^+), suggesting that the films should be intrinsic.

(5) B-doped a-Si:H films for $B_2H_6/SiH_4\geq 1.5x10^{-5}$ make a rectifying contact with Mg and n^+ c-Si, while those films form an Ohmic contact with Au and p^+ c-Si, indicating that majority carriers in those films are holes.

(6) Although the conduction type of B-doped a-Si:H changes from n-type to p-type at $B_2H_6/SiH_4\sim 10^{-6}$ from the study of the