CHAPTER II PROPERTIES OF CONTACTS BETWEEN HYDROGENATED AMORPHOUS SILICON AND OTHER MATERIALS

2-1. Introduction

Studies of metal/semiconductor junctions and heterojunctions are helpful for understanding fundamental device physics as well as for realizing applications to various devices. In other words, it is necessary to recognize whether each contact in a device shows Ohmic behavior or rectifying behavior.

This thesis has investigated the electrical properties of a rectifying junction between an undoped hydrogenated amorphous silicon-based alloy and crystalline silicon (c-Si) in a metal/amorphous/crystalline diode. So, it is necessary to make only one rectifying heterojunction and the other good Ohmic contacts in the diode. In order to get Ohmic contacts with undoped hydrogenated amorphous silicon-based alloys, however, the use of heavily doped hydrogenated amorphous silicon (a-Si:H) should be avoided because of keeping the dopant of heavily doped a-Si:H from contaminating the undoped hydrogenated amorphous silicon-based alloy. This is because the properties of undoped hydrogenated amorphous silicon-based alloys have been investigated by the study of those heterojunctions. Therefore, metal is preferable to an Ohmic-contact material for undoped hydrogenated amorphous silicon-based alloys as long as metal is evaporated onto amorphous films at room temperature.

This chapter has investigated electrical properties of metal(Au,Pt,Al,Mg)/a-Si:H/c-Si(n^+,p^+) diodes and has described the property (Ohmic or rectifying) of each contact. Furthermore, the conduction type of P-doped, undoped, and B-doped a-Si:H has been classified into three categories such as n-type, intrinsic, and p-type from the study of junction properties.

2-2. Contact Properties for Undoped and P-doped a-Si:H

CHAPTER II PROPERTIES OF CONTACTS

Undoped a-Si:H films, ~ 1 μm in thickness, were deposited on n^+ and p^+ c-Si heated to 250 ℃ by the rf glow-discharge decomposition of pure SiH_4. A flow rate of 5 sccm and a gas pressure of 50 mTorr were maintained during the deposition. The dark conductivity at 297 K and its activation energy were 5×10^{-9} S/cm and 0.72 eV, respectively. After depositing a-Si:H films, four different kinds of metals (Mg, Al, Au, Pt) were subsequently evaporated onto different positions of identical a-Si:H films. Current-voltage (I-V) measurements have been performed on those metal/undoped a-Si:H/c-Si structures.

P-doped a-Si:H films were deposited on n^+ c-Si heated to 300 ℃ from PH_3/SiH_4 gas mixture under the gaseous impurity ratios of 3×10^{-4} and 3×10^{-3}, where a total gas-flow rate of 5 sccm and a gas pressure of 50 mTorr were kept constant. Similar measurements have also been done on metal/P-doped a-Si:H/n^+ c-Si specimens.

Figure 2.1 shows the I-V characteristics of the metal/undoped a-Si:H/n^+ c-Si specimens for four different kinds of metals. The essential features of the characteristics of the Au, Pt, and Al specimens are almost the same, while the I-V characteristics of the Mg specimen are quite different from the others.

As is shown in Fig. 2.1, the magnitudes of the currents in the Mg/undoped a-Si:H/n^+ c-Si diode at bias voltages of ± 0.1 V are equal to or larger than 5×10^{-8} A/mm^2 which is simply calculated from the dark conductivity (5×10^{-9} S/cm) and thickness (about 1 μm) of the a-Si:H film, indicating that the current in the Mg specimen must be a bulk-limited current like an Ohmic current or a space-charge-limited current (SCLC). Therefore, both the contacts of Mg/undoped a-Si:H and n^+ c-Si/undoped a-Si:H must behave as an Ohmic contact. This results in an energy-band diagram of Fig. 2.2(b). Although this diode shows a little rectifying property, the Mg/undoped a-Si:H contact could not affect the electrical properties of undoped a-Si:H/p c-Si heterojunctions in Mg/undoped a-Si:H/p c-Si diodes mentioned in the following chapters because the current level studied there is much lower than the Ohmic current level.

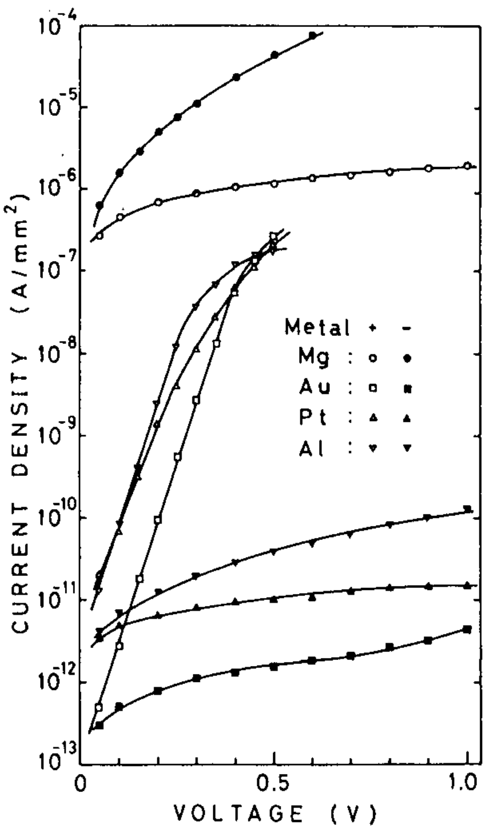

Fig.2.1. I-V characteristics of metal/undoped a-Si:H/n^+ c-Si structures.

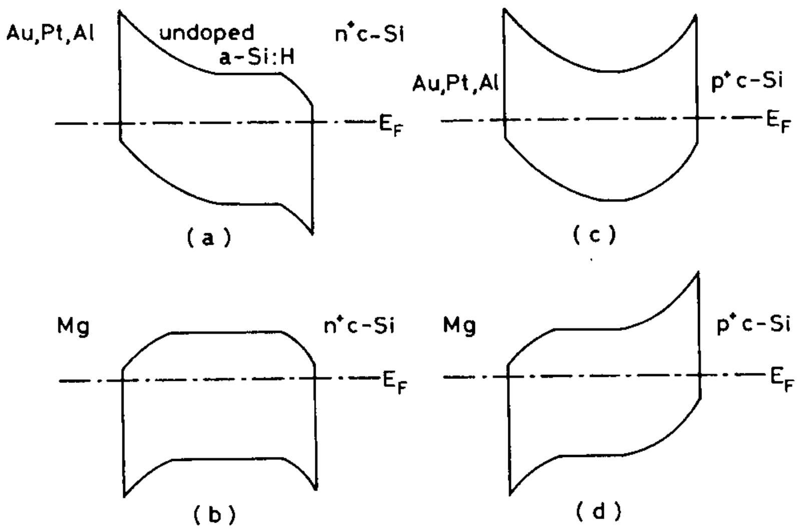

Fig.2.2. Energy-band diagrams of undoped a-Si:H: (a) metal(Au,Pt,Al)/undoped a-Si:H/n^+ c-Si; (b) Mg/undoped a-Si:H/n^+ c-Si; (c) metal(Au,Pt,Al)/undoped a-Si:H/p^+ c-Si; (d) Mg/undoped a-Si/p^+ c-Si.

In contrast to the Mg specimen, the I-V characteristics of the Au, Pt and Al specimens are mainly limited by Schottky barrier junctions formed by metal/undoped a-Si:H contacts, because the n^+ c-Si/undoped a-Si:H contact is found to be Ohmic. Actually, considering the I-V characteristics shown in Fig. 2.1, it is quite reasonable to present an energy-band diagram of undoped a-Si:H for Al, Pt and Au contacts, as is sketched in Fig. 2.2(a). A positive bias voltage on the metal electrodes induces forward currents.

Figure 2.3 shows the I-V characteristics of the metal/undoped a-Si:H/p^+ c-Si specimens. It is considered that the currents of metal(Au,Pt,Al)/undoped a-Si:H/p^+ c-Si specimens for a negative bias on the metals are limited by the reverse-biased metal/undoped a-Si:H contacts, since the magnitudes are of the same order as those of the reverse currents of the corresponding metal(Au,Pt,Al)/undoped a-Si:H/n^+ c-Si specimens shown in Fig. 2.1. On the other hand, the current flowing through each specimen, on applying a positive bias voltage to the metals, is determined by the reverse-biased p^+ c-Si/undoped a-Si:H contact, which is evident from the fact that each value coincides with every other independent of metal electrodes within a small statistical scatter. Consequently, the I-V characteristics of the metal(Au,Pt,Al)/undoped a-Si:H/p^+ c-Si structures are considered to be those of back-to-back diodes with an energy-band diagram shown in Fig. 2.2(c).

Only when a negative bias voltage is applied to the Mg electrode, does the specimen show forward I-V characteristics originating from the property of the p^+ c-Si/undoped a-Si:H contact, since the current level is considerably lower than that of the Mg/undoped a-Si:H contact shown in Fig. 2.1. An energy-band diagram of Fig. 2.2(d) can thus be obtained for the Mg/undoped a-Si:H/p^+ c-Si structure.

From the above experimental results, it is clear that Mg makes a good Ohmic contact with undoped a-Si:H. These experimental results could be discussed in terms of the difference in work functions between metal (ϕ_m) and a-Si:H (ϕ_s). According to the conventional metal/semiconductor

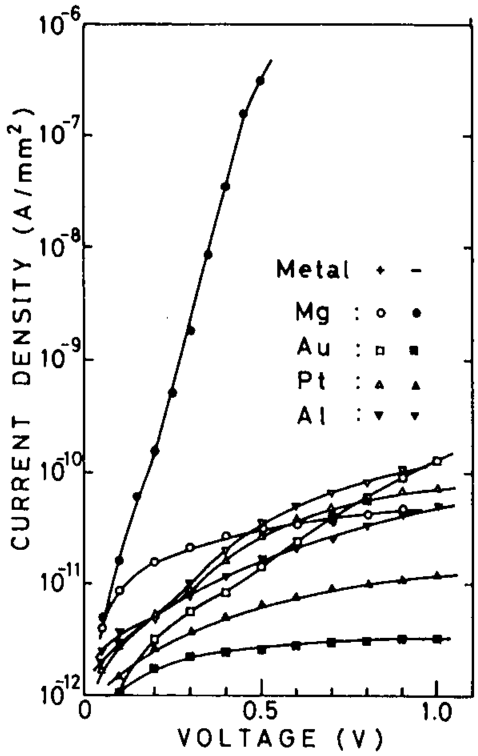

Fig.2.3. I-V characteristics of metal/undoped a-Si:H/p^+ c-Si structures.

junction theory,[1)] the relation

$$\phi_m \leqq \phi_s \qquad (2\text{-}1)$$

should be satisfied for making an Ohmic contact when majority carriers are electrons, as long as its interface states are assumed to be absent.

The work function of each metal used in the present study is 3.46, 4.20, 4.70 and 5.48 eV for Mg, Al, Au and Pt, respectively.[2)] On the other hand, the electron affinity of the a-Si:H (χ_2) can be tentatively estimated from the photoemission data of Yamamoto et al.[3)] on SiO_2/a-Si:H structure, because the electron affinity of SiO_2 [$\chi(SiO_2)$] is independently given as 0.90 eV. Then χ_2 is calculated as

$$\chi_2 = \phi + \chi(SiO_2) = 3.93 \text{ eV} \quad , \qquad (2\text{-}2)$$

where ϕ represents the barrier height at SiO_2/a-Si:H and was estimated to be 3.03 eV.[3)] As will be discussed in Chapter III, the study of the high-frequency capacitance-voltage (C-V) characteristics of undoped a-Si:H/p c-Si heterojunctions will make it possible to estimate χ_2. Since 0.72 eV is the activation energy (δ_2) of the dark conductivity of the present undoped a-Si:H as mentioned above, ϕ_s becomes 4.65 eV because $\phi_s = \chi_2 + \delta_2$.

From the above discussion, both Mg and Al satisfy the condition represented by Eq. (2-1), while the present study indicates that only Mg forms an Ohmic contact with undoped a-Si:H. The observed non-Ohmic property of Al/undoped a-Si:H contacts might be caused by the presence of the interface states.[4)] Namely, ϕ_m of Al is not low enough to make the Al/undoped a-Si:H contact Ohmic.

The metal(Mg,Al)/P-doped a-Si:H contacts for different doping levels of P have also been investigated, as shown in Fig. 2.4. As is clearly indicated, Mg forms better Ohmic contacts than Al regardless of doping levels of P in P-doped a-Si:H. It is likely that Mg is a desirable Ohmic-contact material, superior

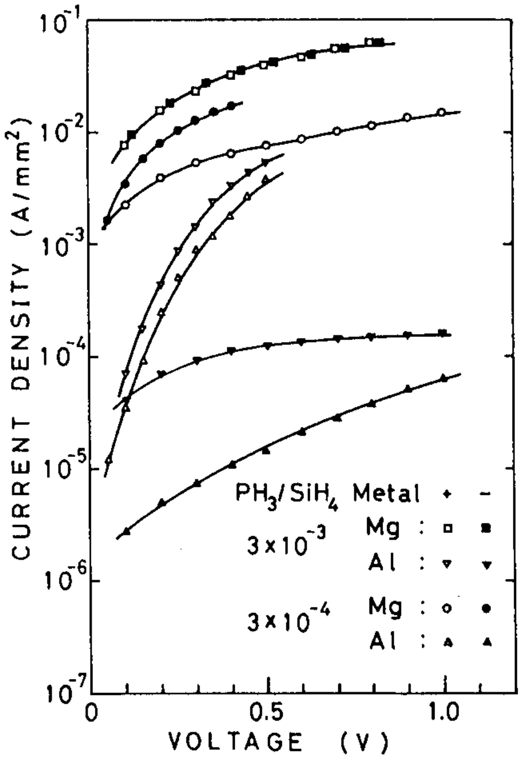

Fig.2.4. I-V characteristics of metal/P-doped a-Si:H/n$^+$ c-Si structures.

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.