perceptible changes in I-V characteristics are observed. This result agrees with an earlier observation of B^+ ion implant damage in Si by nonspectrometric ellipsometry for B^+ doses as low as 3×10^{11} cm^{-2}.[9]

In conclusion, we have shown that Si Schottky barrier characteristics are affected by Ar^+ ion damage at dose levels as low as $\sim5\times10^{11}$ cm^{-2}, about two orders of magnitude below the threshold dose for amorphization of the Si surface. With the ion energy threshold established from earlier experiments at ~25 eV, this work points out fundamental limitations of ion-assisted dry etching processes on Si surface damage.

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Metal-semiconductor junctions and amorphous-crystalline heterojunctions using B-doped hydrogenated amorphous silicon

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Investigated are the current-voltage characteristics of metal (Au, Mg)/B-doped hydrogenated amorphous silicon (a-Si:H)/crystalline silicon (n^+, p^+) diodes for various doping levels of B in a-Si:H. From junction studies we determine the conduction type of B-doped a-Si:H on the basis of "dominant" carrier concentration, and find that the p-n transition occurs at $B_2H_6/SiH_4\sim10^{-6}$ although the conductivity minimum appears at $B_2H_6/SiH_4\sim10^{-4}$.

Studies of metal-semiconductor junctions and heterojunctions of hydrogenated amorphous silicon (a-Si:H) are helpful towards understanding the fundamental device physics as well as for realizing applications to various devices. In earlier work[1-3] we reported systematic studies on several types of junctions made of P-doped a-Si:H as well as undoped a-Si:H. We found that metal (Pt, Au, Al)/a-Si:H Schottky barrier junctions and p^+ crystalline Si(c-Si)/a-Si:H heterojunctions exhibit rectification whereas Mg/a-Si:H and n^+c-Si/a-Si:H junctions are nearly ohmic.

In this letter we present results on the junction properties of metal (Au, Mg)/B-doped a-Si:H/c-Si(n^+,p^+) structures as functions of the B-doping level. We discuss the transport properties, and we characterize the conduction type of each B-doped specimen in terms of carrier concentration.

Crystalline Si wafers were soaked in a solution of HF to remove SiO_2, 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°C by means of 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 lowest dark conductivity of a-Si:H depostied in this way was measured in a planar electrode geometry on Corning 7059 glass substrate, and was found to be around 10^{-12} $(\Omega\text{cm})^{-1}$ at $B_2H_6/SiH_4\sim10^{-4}$. The details of other basic properties of B-doped a-Si:H films have been described elsewhere.[4,5] 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). dc current-density versus voltage (J-V) measurements have been performed for these diodes at room temperature. In our diode structures the depth profile of B concentration in the a-Si:H layer is expected to be flat because 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 1 shows J-V characteristics of diodes (types 1–4) with the a-Si:H films deposited at five different doping levels:

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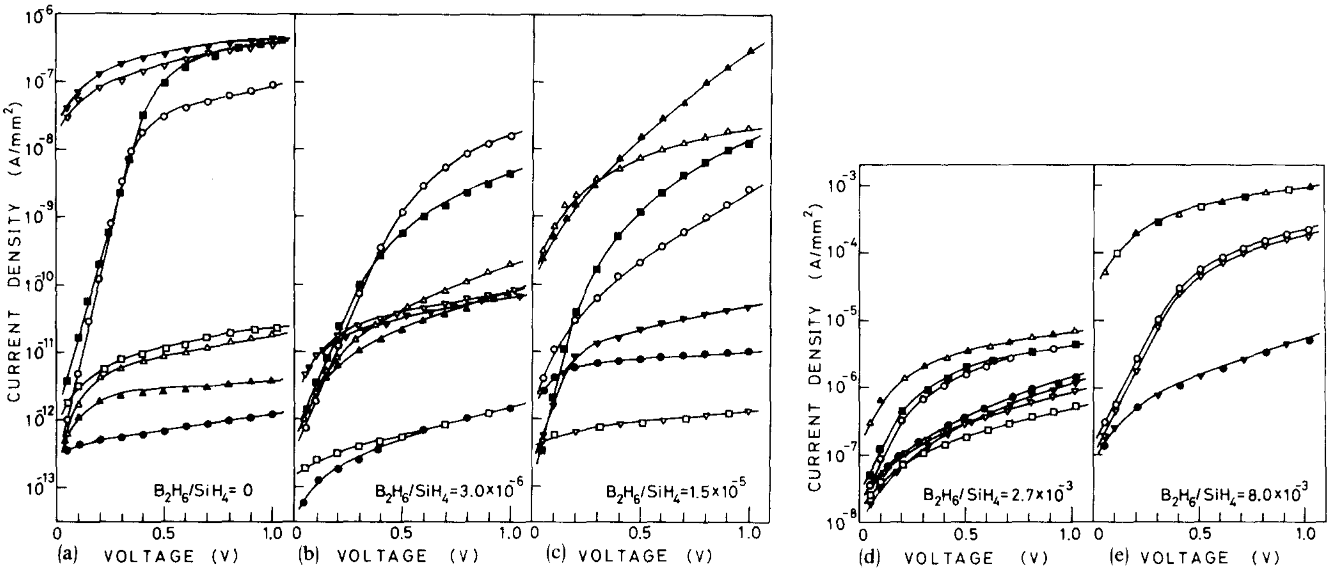

FIG. 1. Current density-voltage characteristics of four different types of diodes: ○ ●, type-1 (Au/*a*-Si:H/n^+*c*-Si); △ ▲, type-2 (Au/*a*-Si:H/p^+*c*-Si); ▽ ▼, type-3 (Mg/*a*-Si:H/n^+*c*-Si); and □ ■, type-4(Mg/*a*-Si-H/p^+*c*-Si). Open mark and solid mark represent data points for a positive bias and a negative bias voltage on the metal, respectively.

(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. 1 (a), type-3 diode shows ohmic behavior and the current level is seen to be 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 nonrectifying. 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 *J-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 "N" (nonrectifying), summarized in the first column of Table I.

Diodes of B-doped *a*-Si:H with B_2H_6/SiH_4 ratios of 7.0×10^{-7}, 1.5×10^{-6}, and 3.0×10^{-6} exhibit similar characteristics, shown in Fig. 1 (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 of Au/*a*-Si:H, Mg/*a*-Si:H, p^+*c*-Si/*a*-Si:H, and n^+*c*-Si/*a*-Si:H are rectifying, as seen in Table I.

From similar analyses of the *J-V* characteristics shown in Figs. 1(c)–1(e), all of the diode junctions have been designated as N or R and are summarized in Table I.

The above results can be discussed in more detail using energy band diagrams for the diodes of types 1–4 shown in Fig. 2. The energy band diagrams were obtained on the basis of previous work[1,2] on undoped *a*-Si:H films, 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,[3] the conduction type of undoped *a*-Si:H is *n*-type, i.e., the majority carriers in un-

TABLE I. 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	N	N	*n*
7.0×10^{-7} 1.5×10^{-6} 3.0×10^{-6}	R	R	R	R	intrinsic
1.5×10^{-5}	N	N	R	R	*p*
2.7×10^{-3}	N	N	R	R	*p*
4.0×10^{-3} 8.0×10^{-3} 1.1×10^{-2}	N	N	N	R	*p*

[a] R: rectification, N: nonrectification.
[b] Based on "dominant" carrier concentration (present study).

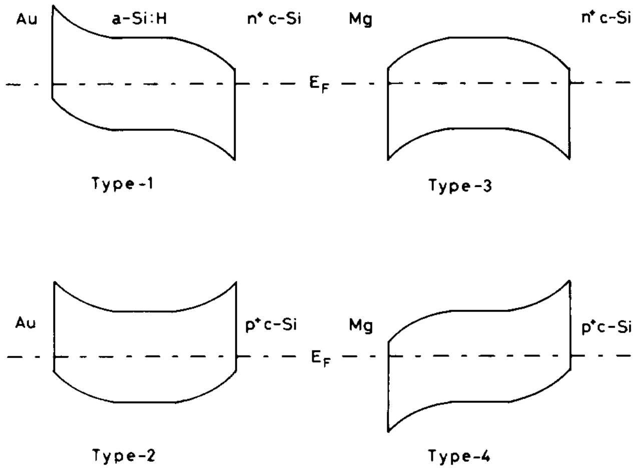

FIG. 2. Energy band diagrams for diodes of types 1–4.

doped *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 I.

For $B_2H_6/SiH_4 \geqslant 1.5\times10^{-5}$, 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 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 nonrectifying when B_2H_6/SiH_4 exceeds 4.0×10^{-3}, which is due probably to tunneling of holes through the very thin Schottky barrier formed by the heavy doping.

In B-doped *a*-Si:H for a doping ratio of $7.0\times10^{-7} \leqslant B_2H_6/SiH_4 \leqslant 3.0\times10^{-6}$, 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 of *a*-Si:H deposited above $B_2H_6/SiH_4 = 1.5\times10^{-5}$ was found to be *p*-type, while the minimum conductivity was found to occur at $B_2H_6/SiH_4 \sim 10^{-4}$, similar to the case of Spear and LeComber.[6] The conductivity minimum should occur at $\mu_p p = \mu_n n$ since 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 the hole concentration p exceeds n at $B_2H_6/SiH_4 = 1.5\times10^{-5}$, $\mu_p p$ is probably still smaller than $\mu_n n$ because $\mu_p \ll \mu_n$.[7-9] Therefore, the value of $\mu_p p$ is closer to that of $\mu_n n$ at $B_2H_6/SiH_4 \sim 10^{-4}$.

Spear and LeComber[6] 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 $B_2H_6/SiH_4 \sim 10^{-4}$. 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 $B_2H_6/SiH_4 > 10^{-5}$.

In summary, we have discussed the nature of metal-semiconductor junctions and amorphous-crystalline heterojunctions for various doping levels of B in *a*-Si:H fabricated using metal (Au,Mg)/B-doped *a*-Si:H/*c*-Si(n^+,p^+) diodes, and we have determined the conduction type of B-doped *a*-Si:H in terms of the "dominant" carrier concentration. The results are

(1) B-doped *a*-Si:H films of $B_2H_6/SiH_4 \geqslant 1.5\times10^{-5}$ form a rectifying contact with Mg and n^+ *c*-Si but not with Au and p^+ *c*-Si, indicating that the majority carriers in those specimens are holes.

(2) B-doped *a*-Si:H deposited in the range of $7\times10^{-7} \leqslant B_2H_6/SiH_4 \leqslant 3\times10^{-6}$ forms a rectifying contact with all of the metals and *c*-Si studied in the present work. This suggests that the films can be considered intrinsic.

(3) On the basis of dominant carrier concentration we have found that B-doped *a*-Si:H exhibits *n*-type, intrinsic and *p*-type conduction for $B_2H_6/SiH_4 < 10^{-7}$, $\sim 10^{-6}$ and $> 10^{-5}$, respectively.

(4) The minimum conductivity appears at $B_2H_6/SiH_4 \sim 10^{-4}$, simply because $\mu_p p$ at that doping level becomes nearly equal to $\mu_n n$.

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