Light-intensity dependence of the staebler-wronski effect in a-Si:H with various densities of defects

Light-Intensity Dependence of the Staebler-Wronski Effect in a-Si:H with Various Densities of Defects

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ABSTRACT

The light-intensity dependence of the photocreation of dangling bonds (DBs) were investigated for a-Si:H films with increasing density of defects before light soaking. Samples in which the density of neutral DBs had been increased by annealing at 400 C for 1 h exhibited a weak light-intensity dependence of the photocreated DBs compared to that for the as-deposited sample. Furthermore, the sample which had been illuminated with a light intensity of 1 W/cm^2 for 1 h also showed a weak dependence. The results can be qualitatively explained by using rate equations for the densities of DBs and floating bonds (FBs) based on the FB-mediated photocreation of DBs. When both the densities of DBs and FBs before illumination increase, the light-intensity dependence of the DB density for a moderate value of the illumination time becomes weaker, qualitatively consistent with the observed results.

INTRODUCTION

The mechanism of the Staebler-Wronski effect in a-Si:H has not yet been clear, despite many efforts for a long time[1]. According to Stutzmann et al.[2], the density of photocreated dangling bonds (DBs) obeys the following relation with r=2 in device quality a-Si:H films,

$$Ns(t)^3 - Ns(0)^3 = AG^r t. \qquad (1)$$

Here, Ns(t) and Ns(0) are the DB densities for illumination-time t and before illumination, respectively, A is a constant, and G is the light intensity. They deduced this equation based on the model in which weak bonds are broken by phonons created by the nonradiative recombination of the photoexcited electrons and holes. Since this work, the illumination-time dependence has been reported by many authors for various a-Si:H films. However, the experimental studies on the light-intensity dependence are less than the illumination-time dependence.

Recently, we reported that the value of r becomes smaller with increasing the N content in a-Si-N:H alloy films[3]. It is known that the density of charged DBs is increased prominently by adding N atoms in a-Si:H besides an increase in the density of neutral DBs[4]. The fact implies that the large change of r in a-Si-N:H alloy films might be due to the presence of the charged DBs. In order to clarify the role of the charged dangling bonds in the Staebler-Wronski effect, we investigated in detail the light-intensity dependence in a-Si:H films with increased densities of neutral DBs. Annealing above 350 C is known to make hydrogen atoms effuse out from a-Si:H and to increase the density of neutral DBs. Photodegradation is another way to increase the density of neutral DBs with no appreciable change in the density of charged DBs[5]. Hence the light-intensity dependence of the photocreated DBs was measured for both kinds of annealed and photodegradated a-Si:H films.

The observed results were discussed by using rate equations for the densities of DBs and floating bonds (FBs) based on the FB-mediated photocreation of DBs[6].

EXPERIMENTALS

a-Si:H films were prepared by glow-discharge decomposition of silane gas with a flow rate of 15 sccm. The nominal substrate temperature was 350 C (the actual temperature should be 250-300 C). The thickness of the film was 1300 nm. The X-band ESR measurements were done at room temperature to obtain the density of neutral DBs. The sample films were annealed at 200 C for 1 h in flowing nitrogen gas before the experiments of light soaking. The density of neutral DBs was 2.0 x 10^{16} cm^{-3} including surface DBs in the annealed state. We call this sample as a standard a-Si:H. In order to get a sample with increased density of neutral DBs, a-Si:H films were annealed at 400 C for 1 h in vacuum. Before starting the light-soaking experiments, the films were annealed at 200 C for 1 h in flowing nitrogen gas as in the case of the sample without 400 C annealing. The neutral DB density before light soaking was 4.2 x 10^{16} cm^{-3} including surface DBs. We call this sample as HTA a-Si:H. Another way to get a sample with the increased density of DBs is the light soaking. Samples light-soaked for 1 h with the light intensity of 1 W/cm^2 has a neutral DB density of 5.1x 10^{16} cm^{-3} including surface DBs.

The light soaking was carried out at room temperature using a white light from a Xe lamp with an IR cut filter. The illumination time was fixed at 1 h or 10 h, and the light intensity was changed using a neutral density filter. In order to avoid the increase in temperature during the light soaking, the sample was mounted on a copper block which was cooled by water.

RESULTS AND DISCUSSION

Figure 1 shows the change in the neutral DB density as a function of the light intensity for the standard a-Si:H. Here the ordinate of the figure is taken as a cubic root of the left hand side of eq. (1). This quantity approaches Ns(t) when Ns(t) is larger than twice of Ns(0). Furthermore the surface DB density was assumed to be unchanged by the light soaking and is subtracted similarly to ref. 7. This is necessary because a large density of surface DBs are known to be present[4], masking a change in the photocreated bulk effect especially in thin a-Si:H films. A density of 1.6 x 10^{16} cm^{-3} was estimated to be contributed from the surface DBs in this sample[7]. In the same manner we treat the bulk density of neutral DBs for other samples in the following. The observed points fit a straight line both for 1- h illumination and for 10-h illumination. The slopes of the straight lines are close to 2/3, being consistent with ref. [2].

The light-intensity dependence of the neutral DB density for a-Si:H annealed at 400 C for 1 h is shown in Fig. 2 for the illumination time fixed at 1 h. Data points roughly fit a straight line, but the slope of the straight line is small compared to those in Fig. 1. A similar decrease in the slope of the light-intensity dependence of the photocreated neutral DBs has been observed in N-incorporated a-Si:H[3]. Adding N atoms in a-Si:H has an effect to increase charged DB density in addition to the increase in the neutral DB density. However, the comparison of the above two results for 400 C annealed and N incorporated a-Si:H makes us to conclude that the charged DBs do not have an essential contribution to the decrease in the slope of the light-intensity dependence of the photocreation of DBs. The increase in the neutral DB density before light-soaking is expected to have an influence on the slope.

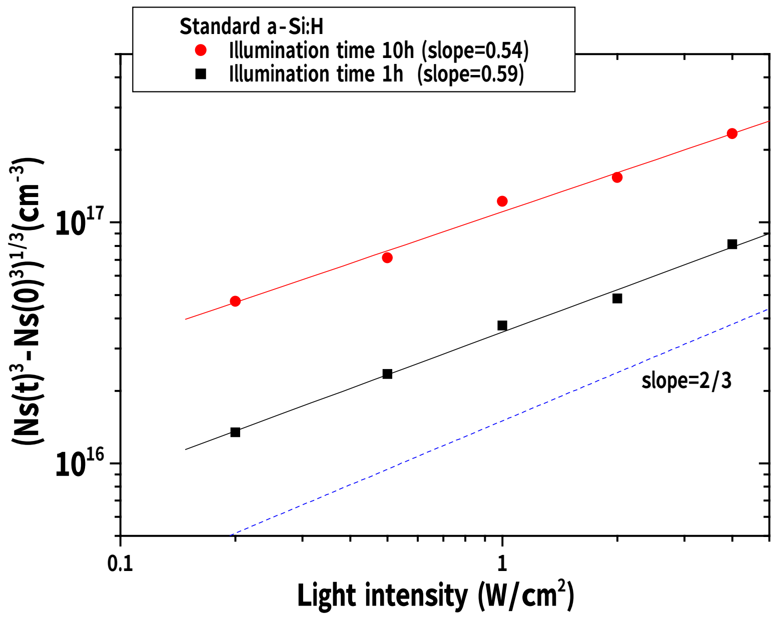

Figure.1 Density of photocreated DBs against the light intensity in standard a-Si:H

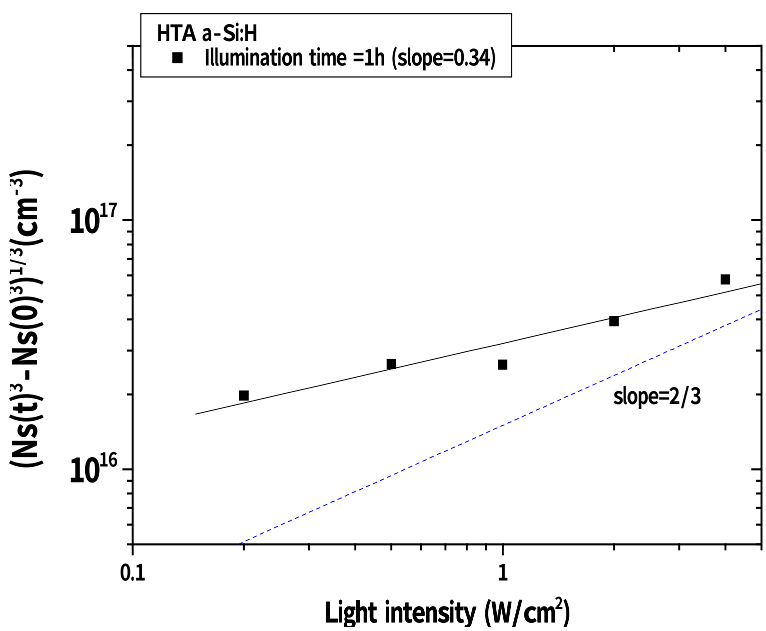

Figure.2. Density of photocreated DBs against the light intensity in a-Si:H annealed at 400 C.

The effect of the increase in the neutral DBs before light soaking is shown in Fig. 3, in which the sample was light-soaked at 1 W/cm^2 for 1 h before the following light-intensity dependence experiments. The slope of the straight line is decreased also for the light-soaked sample similar to the case of the 400 C annealed sample in Fig.2. Since the light soaking is known to increase only neutral DBs and not charged DBs[5], the results suggest that the neutral DB density played a role in changing the light-intensity dependence.

As for the time dependence, the experimental results for a-Si-N:H films and 400-C annealed a-Si:H films show no large deviation from the 1/3 rule.

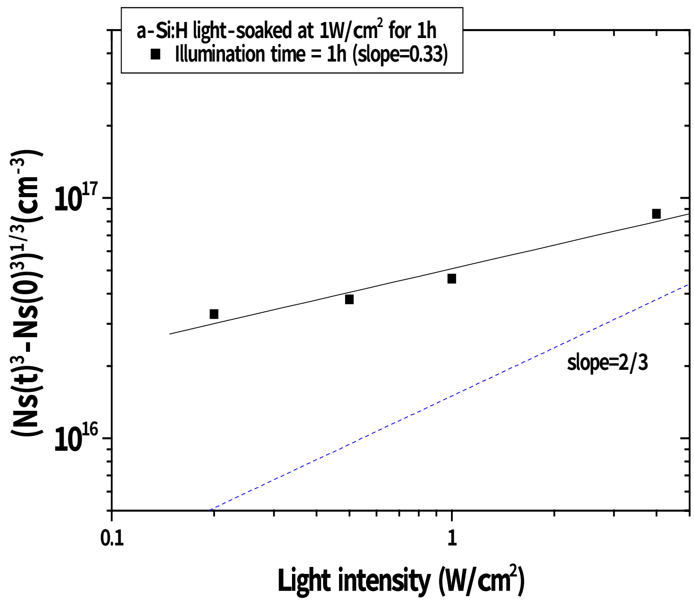

Figure.3. Density of photocreated DBs against the light intensity in a-Si:H light-soaked at 1 W/cm^2 for 1 h.

We tried to explain the observed results by using rate equations for the densities of DBs and FBs based on the FB-mediated photocreation of DBs[6].

$$\frac{dy}{d\tau} = b_1\left(\frac{g}{y}\right)^2 - b_2 gyz + b_3 gz - b_4 gy \tag{2}$$

$$\frac{dz}{d\tau} = b_1\left(\frac{g}{y}\right)^2 - b_2 gyz - b_3 gz + b_4 gy \tag{3}$$

where y and z are the densities of DBs and FBs, respectively, in units of 10^{16}cm^{-3}. g is the carrier generation rate in units of 10^{22} cm^{-3} s^{-1}, τ is time in units of 10^3 s, b_1, b_2, b_3 and b_4 are coefficients independent of y, z, g and τ. The first, second, third and fourth terms on the right-hand side of eqs. (2) and (3) correspond to the creation of a FB-DB pair, the annihilation of a FB-DB pair, the conversion of FB to a DB and vice versa, respectively.

We solved the coupled differential equations (2) and (3) numerically by the fourth order Runge-Kutta method. Figure 4 shows the results of the numerical analysis of the intensity-dependence of the photocreation of DBs. When we choose the initial values of y and z as 0.2 and 0.01, respectively, the time-dependence of the DB density obeys $t^{1/3}$ for the values of g from 0.1 through 2.0 (not shown here). At the same time, the intensity dependences become straight lines with a slope of 2/3 irrespective of the illumination time of 0.1 and 10 as shown in Fig. 4.

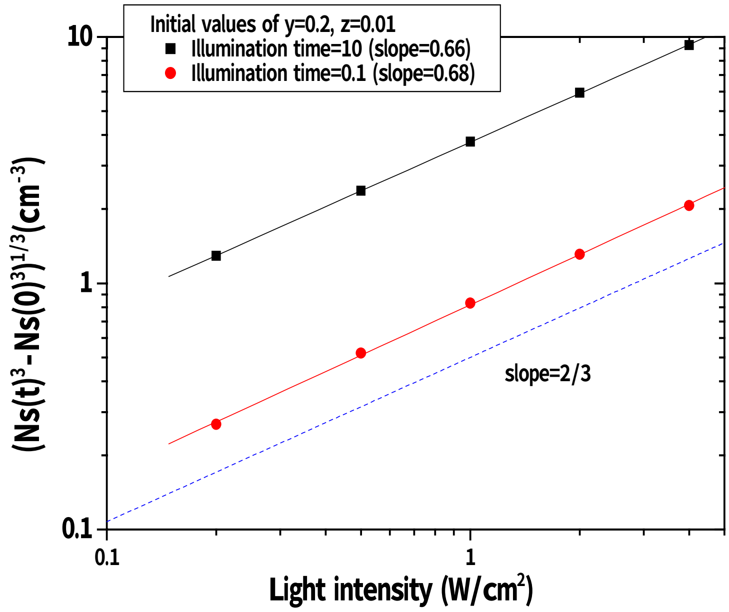

Figure.4. Calculated density of DBs against the light intensity for initial values of y_0=0.2, z_0=0.01.

When the densities of DBs and FBs before illumination are increased to y_0=1.0 and z_0=0.05, the light-intensity dependence of the DB density for the shorter illumination-time becomes weaker as shown in Fig. 5, qualitatively consistent with the observed results. The FB density first increases, having a maximum and then a minimum, and then increases gradually toward the saturated value[6]. After the FB density passes the minimum, the light-intensity dependence of the DB density approaches the normal one with a slope of 2/3 as shown in the upper trace in Fig. 5. The model of Stutzmann cannot explain the present results, and the mediation such as FB is needed for the photocreation of DBs. It is possible that the H-mediated model of Branz[8] can also explain the results.

Based on the simulation results that the light-intensity dependence for the longer illumination time should have a normal slope as shown in Fig. 5, we carried out experiments in which the illumination time was set to 10 h, which was ten times larger than that in Fig. 2. The intensity dependence for 10 h illumination has a larger slope (0.44) than that for 1 h illumination (0.34). The increase in the slope qualitatively agrees with the prediction of the simulation. The value of the slope, however, does not agree with 2/3, probably because 10 h is not sufficient to overcome the minimum point of the FB density.

After the early period in which the calculated FB density shows a maximum, the rate of the increase in y approximately obeys

$$\frac{dy}{d\tau} \cong 2b_1\left(\frac{g}{y}\right)^2 \tag{4}$$

so that the solution

$$y \propto g^{2/3} t^{1/3} \qquad (5)$$

is obtained. When the values of y_0 and z_0 are increased, the above mentioned early period are elongated. That is the reason of the weaker intensity-dependence for a fixed illumination time of 1 h.

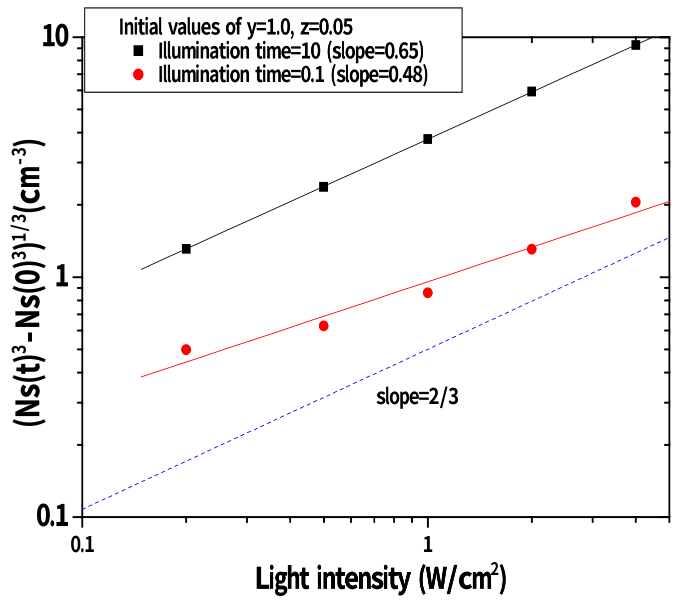

Figure.5 Calculated density of DBs against the light intensity for initial values of y_0=1.0, z_0=0.05.

In summary, the photocreated neutral DBs in a-Si:H has a weaker dependence on the light intensity when the initial values of the DB density have larger values. We can qualitatively explain the results using rate equations based on the model of the FB-mediated creation of DB.

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