# High-temperature light-induced effects in hydrogenated amorphous silicon

Jong-Hwan Yoon
*Department of Physics, College of Natural Science, Kangwon National University, Chunchon, Kangwon-Do, Korea*

Choochon Lee
*Department of Physics, Korea Advanced Institute of Science and Technology, P.O. Box 150, Seoul, Korea*
(Received 29 July 1988)

Light-induced metastable defects are investigated above 200 °C in undoped and hydrogenated amorphous silicon. It is observed that there are two kinds of metastable defects, leading to dark-conductivity and photoconductivity decreases, respectively. Our results suggest that the defects responsible for the photoconductivity decrease are annealed through intermetastable defects which give rise to the increase of the dark conductivity.

## I. INTRODUCTION

One of the particular properties observed in hydrogenated amorphous silicon alloy (*a*-Si:H) is a light-induced metastability called the Staebler-Wronski (SW) effect. Since the effect was found by Staebler and Wronski in 1977,[1] many experimental results and models have been reported.[2–6] As a result, now it is widely accepted that the light-induced metastable defects are annealed at temperatures above 150 °C and that there is more than one kind of metastable defects.[7–9] Han *et al.* have suggested that two kinds of metastable defects are produced by light exposure. One affects primarily the photocarrier lifetime, and the other produces an increase in sub-band-gap absorption.[7] The majority of the studies for the creation and annealing kinetics of metastability has been, however, provided at temperatures below 150 °C. In this Brief Report we present experimental data on the creation and annealing behaviors of the light-induced metastable defects at temperatures above 150 °C. We have observed that the light-induced effects for dark conductivity and photoconductivity exhibit normal SW effects after defect creation, but the annealing behaviors of both are very different from each other. The recovery of dark conductivity overshoots the annealed-state value, and finally decreases slowly to the equilibrium annealed-state value, but that of photoconductivity increases monotonically up to the equilibrium annealed-state value without overshooting above the annealed-state value. We will present some possible mechanisms to explain the results.

## II. EXPERIMENTAL DETAILS

Undoped *a*-Si:H films about 1 $\mu$m thick were deposited at 300 °C in a rf (13.56 MHz) plasma reactor from pure $SiH_4$. Evaporated Al contacts, 3 mm long and separated by 0.2 mm, were used for coplanar conductivity measurements. Light soaking was carried out in vacuum better than $10^{-6}$ torr with ir-filtered white light of 70 mW/cm$^2$ intensity obtained from a tungsten-halogen lamp. The light soaking and annealing changes of the conductivity were measured by exposing the sample to light for 30 min at the elevated temperature, and allowing it to be annealed. All measurements were carried out *in situ* after annealing the samples at 250 °C for 1 h in vacuum. The effects of photoconductivity changes on annealing were measured using the same conditional light as light soaking. Photoconductivity measurements were made by exposure to light for about 1 sec. In this time interval the light-soaking effect was so very small as to be ignored in terms of experimental error.

## III. RESULTS AND DISCUSSION

The light-induced changes in the conductivity of *a*-Si:H were found to return to the original values after annealing at temperatures above 150 °C. This property was studied at high temperature above 150 °C. Figure 1 shows the time dependence of the dark conductivity recovery after light soaking. The initial annealed state was obtained by slowly cooling to 240 °C after annealing for 1 h at 250 °C. The light-soaked state was achieved by prolonged light exposure for 30 min at 240 °C. At this temperature the light-soaked state exhibits the normal SW effect, in which the dark conductivity and photoconductivity are decreased after light soaking. On the other hand, the recovery of Fig. 1 was obtained from dark-conductivity measurements after light exposure and immediate annealing. The horizontal dashed line shows the value of the annealed state dark conductivity. Figure 1 shows that the dark conductivity overshoots the annealed state value and finally decreases slowly to the equilibrium value. This result is also consistent with that observed in doped *a*-Si:H by Deng and Fritzsche.[10] According to the Fermi level shift model for the SW effect[11,12] we ensure that the creation of excess conductivity above the annealed state value is caused by the Fermi level shift towards the conduction-band edge $E_c$ through the annealed-state Fermi level in the annealing process. Also, the existence of a maximum excess conductivity and its slow decrease indicate that the overshoot of the Fermi level above the annealed-state Fermi level should only be caused by converting the existing light-induced

 

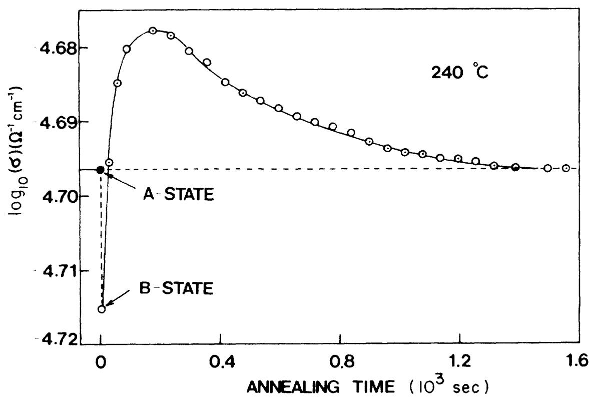


FIG. 1. Time dependence of dark-conductivity recovery at 240 °C after light soaking. The conductivity is measured after light exposure at 240 °C and allowing it to be annealed.

metastable states to other states rather than the creation of new metastable states in the annealing process.

From these facts we suggest that some of the light-induced metastable defects are annealed through intermetastable defects which give rise to the increase of the dark conductivity in the annealing process. This suggestion can also be seen in Fig. 2. Figure 2 shows the time dependencies of the dark conductivity and photoconductivity recovery after light soaking for 30 min at 220 °C and then allowing it to be annealed. The recoveries of the conductivity are normalized by the orignal annealed-state values, respectively. The annealing behavior of the dark conductivity is very similar to that of Fig. 1. On the other hand, the annealing behavior of the photoconductivity is very different from that of the dark conductivity. The photoconductivity monotonically increases with annealing time, and finally its value arrives at the annealed-state value without the creation of excess photoconductivity. Figure 2 shows also that when the dark conductivity recovery ($\sigma_B/\sigma_A$) is 1 (full recovery), the photoconductivity recovery is only about 0.85 (not full recovery). These facts mean that the light-induced metastable defects resulting in dark conductivity and photoconductivity decreases are different from each other, and moreover that some kinds of the metastable defects resulting in the excess photoconductivity above the annealed-state value can never be produced by annealing. This is very different from the annealing behavior of the dark conductivity. In addition, as shown in Fig. 2, we observed also that the time interval required for the light-soaked state photoconductivity to recover fully to the equilibrium annealed-state value agrees with that of the dark conductivity. As a result, we suggest that the original light-induced metastable defects responsible for the photoconductivity decrease are converted to the intermetastable defects which give rise to the increase of the dark conductivity.

The observation of excess dark conductivity above the annealed-state value may be explained on the basis of the light-induced metastable states model suggested by Tanielian *et al.*[13] Figure 3 shows the simplified diagram of gap-state distribution produced by light soaking. The overlapping center of light-induced donorlike and acceptorlike states lies below the annealed-state Fermi level of activation energy 0.75 eV, under which condition the light-soaked state Fermi level will be shifted toward the valence band, resulting in the decrease of the dark conductivity. On the other hand, the photoconductivity decrease after light soaking arises from the increased recombination through the light-induced acceptor states which have a high capture cross section for electrons. In addition, if we assume that the light-induced acceptorlike states are converted to the donorlike states in annealing, then one can observe the shift of the light-soaked state Fermi level towards the conduction band through the annealed-state Fermi level, resulting in the excess dark conductivity and the monotonic recovery of photoconductivity. This explanation is very difficult because there is no experimental or theoretical evidence for such a suggestion.

Finally, we will address the question as to whether these results are a general phenomenon of light-induced metastability which can be observed in all range of temperatures. Figure 4 shows the time dependence of the dark conductivity recovery ($\sigma_B/\sigma_A$) after light soaking

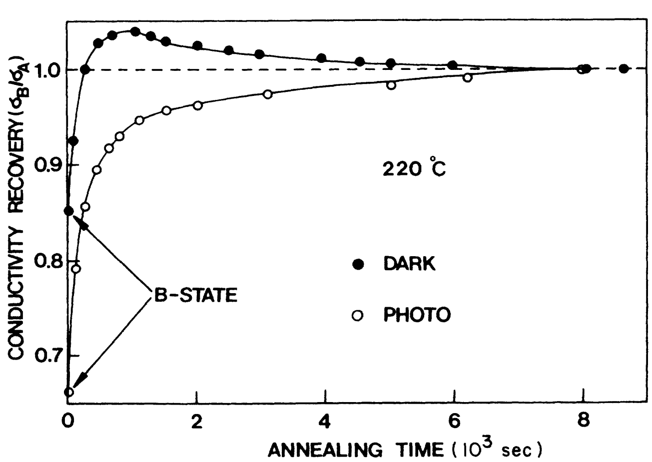


FIG. 2. Time dependencies of dark conductivity and photoconductivity recovery normalized by annealed-state values.

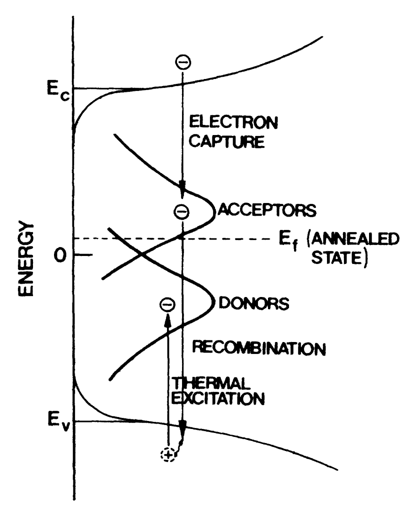


FIG. 3. Schematic density-of-gap states diagram showing the light-induced defect states and the possible trapping transitions.

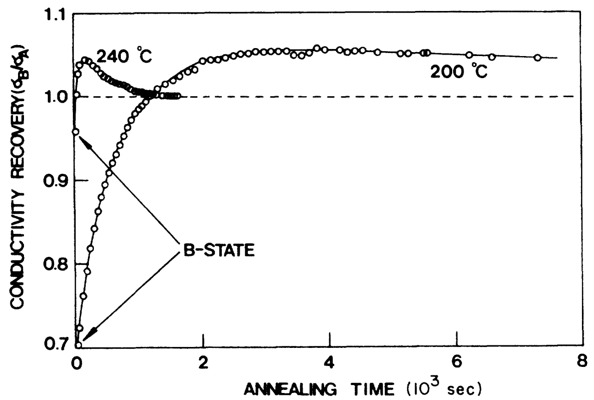


FIG. 4. Time dependencies of the dark-conductivity recovery for different temperatures.

for different temperatures. The annealing behaviors in Fig. 4 show that the time required for full recovery (first annealed-state value) of the light-induced decrease of the dark-conductivity is much longer for low temperature than for high temperature. We cannot therefore, easily observe the same annealing phenomena as shown in Fig. 1 for room temperature, but the same origin for the creation and annealing of light-induced metastable defects is also expected at room temperature.

In conclusion, we have investigated the creation and annealing of the light-induced metastable defects in *a*-Si:H at high temperature. It was observed that the light-induced effects of dark conductivity and photoconductivity exhibit normal Staebler-Wronski effects, but their annealing behaviors are very different. The annealing behavior of dark conductivity shows excess conductivity above the original annealed-state value, but that of photoconductivity shows a monotonic increase to the annealed-state value without the creation of excess photoconductivity in annealing. From these results we have suggested that the light-induced metastable defects responsible for the photoconductivity decrease are annealed through intermetastable defects which give rise to the creation of excess dark conductivity.

## ACKNOWLEDGMENTS

This work was supported in part by the Korea Science and Engineering Foundation.

[1]D. L. Staebler and C. R. Wronski, Appl. Phys. Lett. **31**, 292 (1977).

[2]J. I. Pankove and J. E. Berkeyheiser, Appl. Phys. Lett. **37**, 705 (1980).

[3]D. V. Lang, J. D. Cohen, and J. P. Harbison, Phys. Rev. B **25**, 5285 (1982).

[4]H. Dersch, J. Stuke, and J. Beichler, Appl. Phys. Lett. **38**, 456 (1980).

[5]S. R. Ovshinsky, J. Non-Cryst. Solids **32**, 17 (1979).

[6]P. E. Vanier, Appl. Phys. Lett. **41**, 986 (1982).

[7]Daxing Han and H. Fritzsche, J. Non-Cryst. Solids **59&60**, 397 (1983).

[8]P. E. Vanier, A. E. Delahoy, and R. W. Griffith, J. Appl. Phys. **52**, 5235 (1981).

[9]C. Lee, W. D. Ohlsen, and P. C. Tauler, Phys. Rev. B **36**, 2965 (1987).

[10]X. M. Deng and H. Fritzsche, Phys. Rev. B **36**, 9378 (1987).

[11]C. R. Wronski and R. E. Daniel, Phys. Rev. B **23**, 794 (1981).

[12]C. Lee, in *Proceedings of the First International Photovoltaic Science and Engineering Conference, Kobe, 1984,* edited by Y. Hamakawa (Japan Times, Tokyo, 1984), p. 399.

[13]M. H. Tanielian, N. B. Goodman, and H. Fritzsche, J. Phys. (Paris) Colloq. **42**, C4-375 (1981), Suppl. 10.