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Pulsed-light-induced annealing of metastable defects in hydrogenated amorphous silicon

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Annealing of the metastable defects in hydrogenated amorphous silicon (*a*-Si:H) under pulsed light illumination is reported. It is found that light pulse increases the rate of annealing compared to annealing in the dark, as observed under continuous wave (cw) light. Annealing under cw light with an intensity similar to pulsed light has also been investigated for comparison. Results show that the rate of annealing under pulsed light is lower than under cw light. These results suggest that the rate of the metastable defect creation and the saturation value of the metastable defect density by pulsed light may be higher than by cw light.

Saturation of the light-induced defect density has considerable attraction in the study of the metastability of hydrogenated amorphous silicon (*a*-Si:H). The reason is that the saturation of the metastable defect density cannot only provide us with valuable information for the understanding of microscopic mechanism on the light-induced defect creation, but can also be used as a descriptor to test quickly the completely degraded properties of *a*-Si:H. The observation of the saturation in the light-induced defect creation, even at low temperatures for thermal annealing of defects to be negligible,[1] suggests the existence of a limiting factor, different from the thermal annealing, in the metastable defect creation process. Recently, it has been suggested that the light-induced annealing of the metastable defect may be of practical importance in the saturation of the defect density.[2] Therefore, much theoretical[2,3] and experimental studies[4–9] for the light-induced annealing of metastable defects have been made under cw light illumination. Besides cw light, on the other hand, short light pulses with a pulse width shorter than the excess carrier lifetime have been introduced as an alternative light source for the defect creation by Stutzmann *et al.*[10,11] They have shown that light pulses cause a much faster creation of metastable defects than cw irradiation. They also reported that the metastable defect density induced by pulsed light soaking largely exceeds the saturation value of defect density in the cw case.[10] Using a pulsed laser light, Hata *et al.*[12] studied the saturation behavior of the defect density in *a*-Si:H. They reported that there are no differences between pulsed and cw light-induced saturation values of the defect density even though comparison was not made with the same intensity in both light sources. In order to understand these results, more studies using light pulses are needed. In this work, experimental results on the pulsed light-induced annealing of the metastable defects are presented. Annealing under cw light with an intensity similar to pulsed light has been also investigated for comparison. Results show that the rate of annealing under light pulse is lower than under cw light. On the basis of the kinetic models for metastability including the light-induced annealing term, these results suggest that the rate of the metastable defect creation and the saturation value of the metastable defect density by pulsed light soaking may be higher than by cw light soaking.

The *a*-Si:H film used in this experiment was prepared from undiluted silane gas in a dc-triode glow-discharge reactor on Corning 7059 glass substrates at a substrate temperature of 220 °C. The deposition was carried out in 10 SCCM (cubic centimeter per minute at STP) flow at 650 mTorr pressure and 0.12-W/cm^2 power density. The sample had a thickness of 1.85 μm, a Tauc gap of 1.70 eV, and an annealed state defect density of 5.9×10^{15} cm^{-3}. The light source for the pulsed light soaking and the pulsed light-induced annealing was a Nd:YAG (yttrium aluminum garnet) pumped dye laser, which generates a pulsed light of wavelength of 645 nm with a pulse duration of about 6 nsec and a repetition rate of 10 Hz. Light-induced annealing of defects was monitored by measuring the change of photoconductivity and subgap defect density in a coplanar electrode configuration. Photoconductivity was generated by using uniformly absorbed light ($\lambda=650\pm20$ nm) with an illumination intensity of 3 mW/cm^2 filtered through a band pass filter from a tungsten-halogen lamp. The annealed-state photoconductivity of the sample was 1.1×10^{-5} S/cm. The subgap defect density was measured by the constant photocurrent method (CPM) using a conversion factor of 1.9×10^{16} cm^{-2} eV^{-1}.[13] For the annealing experiments, the sample was attached using high thermal conductive paste to a thermoelectric heater/cooler. The sample temperature during dark and light annealing was controlled within ±0.5 °C accuracy.

Figure 1 shows the CPM spectra of subband gap absorption coefficient measured at room temperature for different sample states, light-soaked or annealed state. The light-soaked state was the pulsed light-induced saturated state, which was achieved by using a pulsed laser light with an average intensity of 300 mW/cm^2 at room temperature. The light soaking was carried out for 6 h for saturation. In order to carry out each annealing experiment with saturated state, after one experiment was finished, the sample was annealed for 2 h at 180 °C in dry nitrogen to restore the fully annealed state, and was resaturated for another annealing experiment. The defect density of the light-soaked saturated state was 3.7×10^{17} cm^{-3}. The annealed states in Fig. 1 were obtained from the annealing of the saturated state for 1 min at 120 °C either in the dark or under pulsed light illumination. Annealing was done in dry nitrogen gas. The increasing and decreasing rates of temperature to and from 120 °C respectively, were kept to be nearly the same as 1.6 °C/sec for both

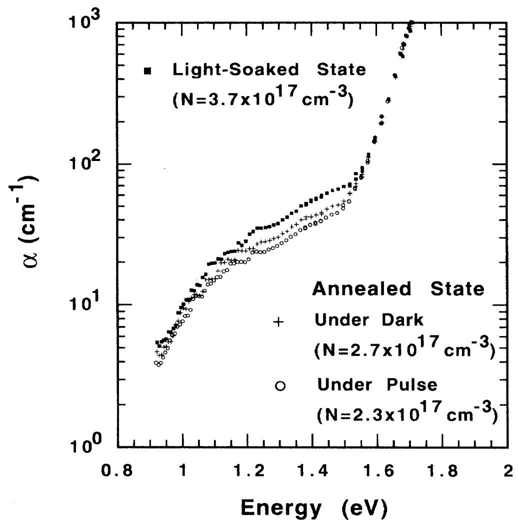

FIG. 1. The subband gap absorption as a function of photon energy for different sample states from CPM measurements. The light-soaked state is the pulsed light-induced saturated one. The annealed states are obtained from the annealing of the saturated state for 1 min at 120 °C in the dark or under pulsed light illumination which average intensity is 10 mW/cm^2.

annealing experiments. After the sample temperature reaches 120 °C, the annealing was performed with or without the pulsed light, which intensity was 10 mW/cm^2. Despite the annealing of the sample for a short time, the result in Fig. 1 shows that pulsed light illumination increases the rate of annealing compared to dark annealing, as observed under cw light illumination.[5,9] The defect densities were 2.7×10^{17} and 2.3×10^{17} cm^{-3} after annealing in the dark and under pulsed light illumination, respectively.

Pulsed light-induced annealing under different average intensities (10 and 30 mW/cm^2), which were varied by changing the energy per pulse rather than the pulse repetition rate, has been studied. The result was plotted as a function of annealing time in Fig. 2. Because of no great change in the metastable defect density by the CPM at each annealing time, the change in photoconductivity was also monitored along with the measurement of the change in the defect density. Figure 2 shows the recovery of photoconductivity measured at room temperature after annealing of the sample at 120 °C in the dark or under pulsed light illumination with different intensities. The initial state was the pulsed light-induced saturated one. Experimental conditions were the same in Fig. 1. It is seen in Fig. 2 that at the beginning of annealing, the annealing proceeds faster at high intensity rather than at low intensity, and it is slowest in the dark. The fact that the recovery rates of photoconductivity under light illuminations are higher than in the dark condition indicates that the defect annealing is also accelerated by pulsed light illumination, as observed under cw light illumination by several workers.[5,8,9] Successive annealing, however, results in the continuing recovery of photoconductivity in the dark but the gradual decrease of the recovery rates under light illuminations, and finally, the rate of annealing in the dark exceeds the rates under light illuminations. In particular, the data

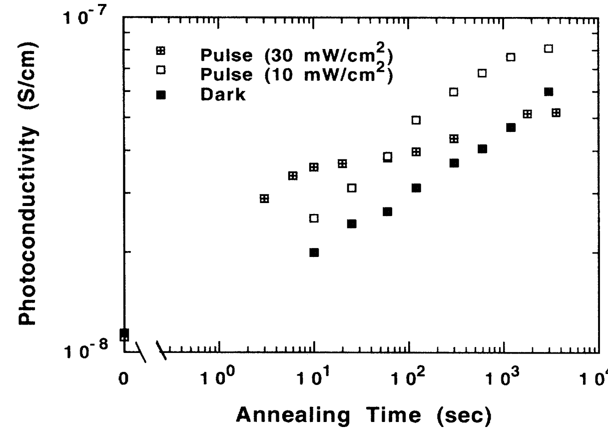

FIG. 2. Room-temperature photoconductivity plotted as a function of annealing time. The initial state is the pulsed light-induced saturated one. Annealing was performed at 120 °C in the dark or under pulsed light illumination with average intensity 10 and 30 mW/cm^2 pulsed laser light.

show that the decrease of the recovery rate in photoconductivity under high intensity illumination occurs at the annealing time less than under low intensity illumination. These results may be caused by the light-induced defect recreation process with light-induced annealing of defects.

Finally, we will address the difference in the light-induced annealing between pulsed and cw light illumination. Figure 3 shows the recovery behaviors of room-temperature photoconductivity plotted as a function of annealing time. Annealing was performed at 120 °C under cw or pulsed light illumination. The same sample in Figs. 1 and 2 was used, and the light-soaked states for annealing experiments were also the pulsed light-induced saturation states. To perform each annealing experiment with a nearly identical initial state, the

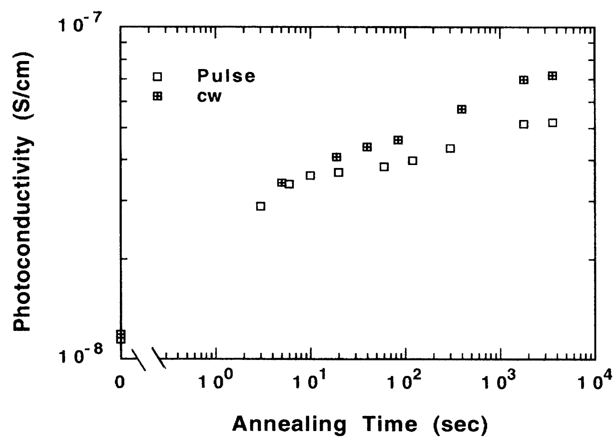

FIG. 3. Room-temperature photoconductivity plotted as a function of annealing time. The initial state is the pulsed light-induced saturated one. Annealing was performed at 120 °C under pulsed and cw light illumination. Illumination intensities are the same in both cases, 30 mW/cm^2.

sample was resaturated by the pulsed light illumination after fully annealed at 180 °C. In both cases, the saturated defect densities and the photoconductivities were nearly the same, which were about 3.7×10^{17} cm^{-3} and 1.2×10^{8} S/cm, respectively. A light intensity of 30 mW/cm^2 filtered through a 650 ± 20-nm band pass filter from a tungsten-halogen lamp was used for the cw light-annealing experiments. The pulsed laser light of an average intensity of 30 mW/cm^2 was also employed for the pulsed light-annealing experiments. Annealing was performed at a temperature of 120 °C in dry nitrogen gas. Figure 3 shows that the light-induced recovery rates of photoconductivity differ in the pulsed and cw light annealing. It is seen in Fig. 3 that photoconductivity under pulsed light illumination is lower than under cw light illumination. This suggests that the light-induced annealing of defects by the pulsed light is also lower than by cw light. This fact is very surprising. Recently, several models including the light-induced annealing term in the kinetics of metastable defect creation and annealing have been proposed.[2,3,8] It has been suggested that a steady-state or saturation behavior in the defect density would be caused by an establishment of a balance between light-induced creation and annealing rates. The experimental data, that is, light intensity dependence of the saturated defect density, can be reasonably explained by the models. Furthermore, according to these suggestions, for the light sources with the different light-induced annealing rates, the different saturation value in the defect density would be also expected. The recent observation of a faster defect creation rate and a higher value in the saturated defect density in using light pulses compared to cw light[8,10] may be caused by the lower light annealing rate in light pulses compared to cw light, as shown in Figs. 1 and 2.

In summary, we have studied the light-induced annealing of defects under pulsed light illumination. Our results show that light pulse also increases the annealing rate as observed in the continuous light illumination. Annealing under continuous light illumination with an intensity similar to pulsed light has been studied. It has been observed that the light annealing rate under pulsed light illumination is lower than under the cw light.

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[1] M. Isomura, N. Hata, and S. Wagner, in *Amorphous Silicon Technology—1991*, edited by A. Madan, Y. Hamakawa, M. Thompson, P. C. Taylor, and P. G. LeComber, MRS Symposia Proceedings No. 219 (Materials Research Society, Pittsburgh, 1991), p. 27.

[2] Z. Y. Wu, J. M. Siefert, and B. Equer, J. Non-Cryst. Solids **137&138**, 227 (1991).

[3] D. Redfield, Appl. Phys. Lett. **49**, 1517 (1986).

[4] R. Meaudre and M. Meaudre, Phys. Rev. B **45**, 12 134 (1992).

[5] M. Isomura and S. Wagner, in *Amorphous Silicon Technology—1992*, edited by M. J. Thompson, Y. Hamakawa, P. G. LeComber, A. Madan, and E. A. Schiff, MRS Symposia Proceedings No. 258 (Materials Research Society, Pittsburgh, 1992), p. 474.

[6] G. Ganguly, Appl. Phys. Lett. **60**, 874 (1992).

[7] A. E. Delahoy and T. Tonon, in *Stability of Amorphous Silicon Alloy Materials and Devices*, edited by B. L. Stafford and E. Sabisky, AIP Conf. Proc. No. 157 (AIP, New York, 1987), p. 263.

[8] C. F. O. Graeff, R. Buhleier, and M. Stutzmann, Appl. Phys. Lett. **62**, 3001 (1993).

[9] H. Gleskova, P. A. Morin, and S. Wagner, Appl. Phys. Lett. **62**, 2063 (1993).

[10] M. Stutzmann, J. Nunnenkamp, M. S. Brandt, and A. Asano, Phys. Rev. Lett. **67**, 2347 (1991).

[11] M. Stutzmann, J. Nunnenkamp, M. S. Brandt, A. Asano, and M. C. Rossi, J. Non-Cryst. Solids **137&138**, 231 (1991).

[12] N. Hata, G. Ganguly, S. Wagner, and A. Matsuda, Appl. Phys. Lett. **61**, 1817 (1992).

[13] Z. E. Smith, V. Chu, K. Shepard, S. Aljishi, D. Slobodin, J. Kolodzey, S. Wagner, and T. L. Chu, Appl. Phys. Lett. **50**, 1521 (1987).