Suppression of the Staebler–Wronski effect in hydrogenated amorphous silicon by ion implantation of gallium and arsenic

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The photoinduced changes in the dark conductivity and the photoconductivity (the Staebler–Wronski effect) have been studied in hydrogenated amorphous silicon after implantation of gallium and arsenic ions. The results show that the implantation substantially reduces the effect of light on the photoelectric characteristics of *a*-Si:H.

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Prolonged illumination of hydrogenated amorphous silicon (*a*-Si:H) in the fundamental absorption region causes a decrease in the photosensitivity of this material (this is the Staebler–Wronski effect[1]). In this letter we are reporting a study of the photoelectric properties of *a*-Si:H films before and after ion implantation of gallium and arsenic for various durations of the illumination.

The *a*-Si:H films, 1.0–1.5 μm thick, were grown by decomposing silane (Ar + 4% SiH_4) in an rf discharge on a glass substrate at 200° C. Optical absorption measurements yielded a value of 1.75 eV for the energy gap of the original films; this value corresponds to a hydrogen concentration of 12% in the *a*-Si:H (Ref. 2). The dark resistivity of these films reached 10^6 Ω · cm. For the implantation of 90-keV ^{69}Ga and ^{75}As ions the target was near room temperature; the implantation doses were 8×10^{14}, 3×10^{15}, and 8×10^{15} cm^{-2} at an ion beam current density of 1.5 $\mu A/cm^2$. Calculations put the average concentration of implanted Ga and As atoms in the range $8 \times 10^{19} - 8 \times 10^{20}$ cm^{-3} in a region about 0.1 μm thick.[3] The films had to be annealed in order to achieve ordered *a*-Si:H:Ga and *a*-Si:H structures after the implantation; this annealing was carried out in an evacuated quartz cell at 300° C for 30 min. (The deposition of *a*-Si:H at a substrate temperature of 250–300° C minimizes the density of localized states in the energy gap.[4]) The films were illuminated with a 500-W incandescent lamp (20 cm from the sample).

Figure 1 shows how the dark resistance R_d and the photoresistance R_{ph} vary with the illumination time after annealing at 300° C. Curves 1 and 1′ correspond to the original *a*-Si:H film; curves 2 and 2′ correspond to films in which gallium had been implanted; and curves 3 and 3′ correspond to films in which arsenic had been implanted. The original *a*-Si:H films exhibit sharp increases in R_d and R_{ph} during the first 30 min, followed by a region of a slower increase until saturation is reached. The values of R_d and R_{ph} in the original films increase by a factor of 8–10. For the films with the implanted atoms, the effect of the illumination on R_d and R_{ph} is far weaker than in the original *a*-Si:H; the magnitude of the effect depends on the chemical nature of the impurity. In *a*-Si:H:Ga, for example, R_d and R_{ph} increase by factors of 2 and 4.5, respectively, while the factors for *a*-Si:H:As are 1.5 and 2.5. The illumination actually has less effect in the films with the implanted atoms, since the thickness of the region in which essentially all the light is absorbed is greater than

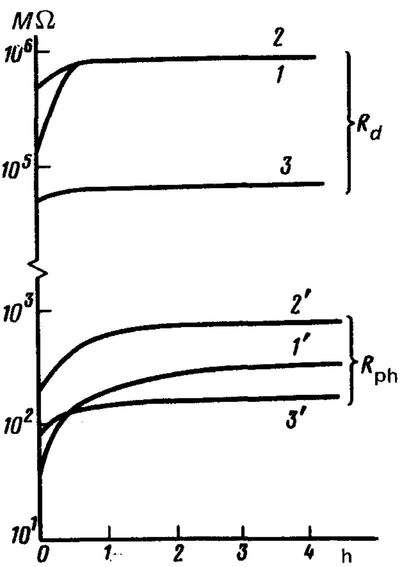

FIG. 1. Variation of the dark resistance and the photoresistance with the illumination time (illumination with white light). 1, 1′–*a*-Si:H films; 2,2′–*a*-Si:H:Ga films; 3,3′–*a*-Si:H:As films. (The doses of Ga and As ions were 8×10^{15} cm^{-2}.)

that of the region containing the implanted Ga and As atoms (about 0.5 μm in comparison with 0.1 μm).

The results show that the implantation of gallium and, especially, arsenic substantially reduces the Staebler–Wronski effect; the effect vanishes nearly completely at an average arsenic concentration of about 10^{21} cm^{-3} in the impurity layer. The photoinduced changes in R_d and R_{ph} observed in the original films can be attributed to a structural "disordering," for which the mechanism is not clear. If the structural defects caused by the illumination correspond to a deep energy level of an acceptor nature, then the Fermi level in the illuminated films will shift toward the center of the energy gap. On the other hand, the decrease in the photosensitivity in the intrinsic region and the essentially zero photoconductivity signal in the impurity region after prolonged illumination imply a shortening of the lifetime of the minority charge carriers. This shortening can be attributed to an increase in the concentration of recombination centers (structural "defects") produced by the light or to a change caused in the electron-capture cross section of multiply charged centers present in the original *a*-Si:H film by a shift of the Fermi level.

The fact that the width of the energy gap and the infrared absorption intensity at the maxima corresponding to vibrations of the Si-H or Si–H_2 bonds do not change upon illumination of the *a*-Si:H, *a*-Si:H:Ga, and *a*-Si:H:As films indicates that there are no important structural defects in the films (no rupture of chemical bonds, no formation of complexes including H atoms, etc.). Further evidence for this conclusion comes from the low annealing temperature, $\gtrsim$150° C (i.e., the low activation energy), at which the photoinduced changes in R_d and R_{ph} disappear. It might be suggested that the illumination of *a*-Si:H causes a structural change in a configuration incorporating an Si–H bond, because a hydrogen atom jumps to another position, further from equilibrium, and there is a reorientation of the Si:H bond. The new configurations (structural "defects") correspond to a deep acceptor level in the energy gap (and, possibly, to a different local vibration mode), and the appearance of this level causes the observed changes in R_d, R_{ph}, and the photosensitivity. The implantation of Ga and As atoms leads to an elastic strain in the nearest neighborhood of the Si–H bond, without any important changes in the electronic or vibrational properties of the configuration as a whole, so that the Si–H bond becomes more stable with respect to light (the Staebler–Wronski effect is weakened) and also with respect to heat treatment (there is an increase in the hydrogen "exodiffusion" temperature[5]). The stabilization of the Si–H bonds caused by the ion implantation of Ga or As ultimately leads to an effective increase in the concentration of equilibrium configurations incorporating Si–H bonds and thus leads to the observed increase in the optical gap width.[5] The high concentration of implanted Ga and As atoms (about 2% in comparison with 12% for H) and the large covalent radius (0.127 and 0.121 nm, in comparison with 0.05 and 0.117 nm for H and Si, respectively) furnish further evidence that elastic strain occurs in the *a*-Si:H:As and *a*-Si:H:Ga films.

In summary, ion implantation of Ga and As can apparently suppress the Staebler–Wronski effect considerably and thus increase the life expectancy of a solar cell made from hydrogenated amorphous silicon.

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