RADIATION TOLERANCE OF BORON DOPED DENDRITIC WEB SILICON SOLAR CELLS

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SUMMARY

The potential of dendritic web silicon for giving radiation hard solar cells is compared with the float zone silicon material. Solar cells with n^+-p-p^+ structure and ~15% (AM1) efficiency were subjected to 1 MeV electron irradiation. Radiation tolerance of web cell efficiency was found to be at least as good as that of the float zone silicon cell. The study of the annealing behavior of radiation-induced defects via deep level transient spectroscopy revealed that E_V + 0.31 eV defect, attributed to boron-oxygen-vacancy complex, is responsible for the reverse annealing of the irradiated cells in the temperature range of 150-350°C.

INTRODUCTION

Important considerations for improving efficiency and radiation hardness of silicon solar cells include high purity silicon, proper cell design, and careful cell processing. High efficiency (ref. 1,2) is very important for both terrestrial and space solar cells, however, solar cell life is drastically reduced in space by the exposure to the radiation environment unless some means is provided to restore the radiation damage (ref. 3,4). For high efficiency silicon crystal growth should keep the level of metal impurities at its minimum because they can reduce the carrier lifetime (ref. 5,6) and degrade the cell performance. The level of other impurities, such as carbon and oxygen, should also be minimized for the radiation hardness because they are known to form complexes with dopants and radiation-induced point defects and give rise to recombination centers (ref. 7,8). Dendritic web silicon is a single crystal ribbon which offers several advantages for producing low cost and radiation hard solar cells. This paper will compare these web features with float zone silicon. For better understanding of the radiation effects, we have used deep level transient spectroscopy (ref. 9) to delineate the radiation-induced traps and study their annealing behavior.

EXPERIMENTAL

Silicon Dendritic Web Growth

Web is a ribbon form of single crystal silicon which is shaped by crystallographic and surface tension forces rather than by potentially contaminating dies. Web crystal for solar cells is generally grown 2-8 mils thick, 2-5 cm wide, and several meters in length. The web results from freezing of a liquid silicon film supported between two bounding dendrites (ref. 10) with the general geometry shown in figure 1. The web can be grown very thin (~2 mils), which makes it cost effective and very attractive for radiation hard solar cells. The surfaces of the ribbon are nearly perfect crystallographic (111) facets which require only minimal cleaning procedures and no mechanical treatments prior to device fabrication. The growth apparatus is relatively simple: a furnace chamber and a molybdenum susceptor which holds the fused quartz crucible; a molybdenum lid assembly with a slot through which the ribbon is withdrawn; and a reel which serves both as a pull mechanism and material storage. Heat is introduced into the system by induction coupling to the molybdenum susceptor. Melt replenishment permits essentially continuous growth.

Cell Fabrication

A large number of n^+-p-p^+ solar cells were fabricated by a diffusion process on several different p-type, boron-doped, web crystals in the resistivity range of 1-10 Ω-cm. The precleaned web crystals along with a few boron doped (111) float zone wafers (10-15 Ω-cm) were phosphorous diffused at 850°C for 35 minutes for the front junction and the p^+ back surface field was formed by boron diffusion at 950°C for 20 minutes. No special attempts were made to obtain high efficiency cells. The n^+ junction depth was approximately 0.35 μm and the sheet resistance was 60 Ω/□. A mixed oxide, TiO_2-SiO_2, antireflective coating was applied on the front by a spin-on process. The cells with an area of 1.03 cm^2 were metallized with Ti-Pd-Ag using an electron-beam system and then mesa etched. The front pattern was a five-finger grid with 5.4% area coverage. Solar cells were tested under illumination from a quartz-iodide simulator which was set at 91.6 mW/cm^2 using a NASA-Lewis calibrated standard cell.

Electron Radiation and Deep Level Transient Spectroscopy

Radiation tolerance of the cells was investigated by subjecting them to 1 MeV electron radiation in the fluence range of 10^{13} - 5 x 10^{15} electrons/cm^2. Deep level transient spectroscopy was used to determine the trap levels generated by electron irradiation. In order to conduct the DLTS measurements, the solar cells were subdivided into 30 mil diameter mesa diodes with Ti-Au contacts. For the annealing studies, DLTS samples and solar cells were simultaneously subjected to heat treatment in air, in 50°C steps, in the temperature range of 100-450°C, the annealing time was 30 minutes at each temperature.

RESULTS AND DISCUSSION

Figure 2 shows the effect of 1 MeV electron radiation on the parameters of a web and a float zone silicon cell. The dopant (boron) concentration in the float zone silicon was four times smaller than in the web and both cells were about 8 mils thick. The data show that 1 MeV electron radiation, beyond a dose of 10^{13} electrons/cm^2, begins to impair the cell performance. It is noteworthy that web cells, in spite of higher boron concentration, are at least as radiation tolerant as the float zone silicon cells. Table 1 shows that after a dose of 10^{15} electrons/cm^2 three deep levels, at E_V + 0.21 eV, E_V + 0.37 eV and E_C - 0.24 eV, were observed in the float zone silicon cell as well as in the web cell. E_V + 0.21 eV level is associated with divacancy and E_V + 0.37 eV and E_C - 0.24 eV levels are attributed to vacancy-carbon-oxygen and interstitial oxygen-boron complexes, respectively (ref. 7). These data show that the rate of introduction and the concentration of the divacancy and the carbon related center is nearly the same in both the cells. Schott et al. (ref. 8) reported that the rate of introduction of carbon related center was higher in the crucible-grown material compared to a float zone material. This suggests that carbon content of the web may be less than other crucible-grown materials, like Czochralski silicon, because there are no graphite components in the web growth system. Most notable difference, however, is about an order of magnitude smaller concentration of the interstitial boron-oxygen defect (E_C - 0.24 eV) in the float zone silicon after the 1 MeV electron irradiation. Since the boron content of the float zone material is low only by a factor of four, the order of magnitude lower concentration of the E_C - 0.24 eV trap suggests higher oxygen content in the web compared to the float zone silicon. This is expected because web is grown from a silicon melt which is in contact with a fused quartz crucible.

Table 1 shows that after 5 x 10^{15} electrons/cm^2 radiation three more deep levels, at E_V + 0.31 eV, E_V + 0.54 eV and E_C - 0.17 eV, were detected in float zone silicon, and one more level, at E_C - .17 eV, was observed in the web cell, in addition to the E_V + 0.21 eV, E_V + 0.37 eV and E_C - 0.24 eV traps. Figure 3 shows that the response of these radiated cells to isochronal annealing is very similar. The data show a reverse annealing of the cells in the temperature range of 150-350°C. The cell efficiency drops by about 1% in the temperature range of 150°C-250°C and stays constant until about 350°C, before the rapid recovery begins. The recovery is not complete even after 450°C anneal if the damage is extensive (5 x 10^{15} electrons/cm^2). Figures 4 and 5 show the annealing behavior of the traps present in the web and float zone silicon cells after 5 x 10^{15} electrons/cm^2 radiation. Most noteworthy is the behavior of E_V + 0.31 eV trap which grows in the temperature range of 150-250°C, stays constant until 350°C and anneals out at approximately 400°C. Figure 6 shows more clearly that these data strongly indicate that E_V + 0.31 eV level, attributed to boron-oxygen-vacancy complex, is responsible for the reverse annealing.

CONCLUSIONS

Dendritic web silicon is capable of producing solar cells with radiation tolerance comparable to the float zone silicon cells. From the densities of carbon and oxygen-related cneters, E_V + 0.37 eV and E_C - 0.24 eV, respectively, we conclude that carbon content of the web is as low as float zone silicon but the oxygen content is higher. Annealing of the electron-irradiated solar cells show an appreciable drop in the cell efficiency in the temperature range of 200-350°C, prior to the cell recovery. E_V + 0.31 eV trap, generally attributed to boron-oxygen-vacancy complex, is found to be responsible for this reverse annealing.

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TABLE 1

Energy levels and concentrations of defects observed in 10 Ω-cm, boron-doped, float zone silicon solar cell and 3 Ω-cm, boron doped, web solar cell after 1 MeV electron irradiation

Energy level (eV)	Defect Concentration (cm^{-3}) 10^{15} e/cm^2 irradiation		Defect Concentration (cm^{-3}) $5 \times 10^{15} e/cm^2$ irradiation	
	FZ silicon cell	Web cell	FZ silicon cell	Web cell
E_V+0.21	1.40×10^{12}	1.20×10^{12}	2.1×10^{13}	2.8×10^{13}
E_V+0.31	-	-	2.0×10^{12}	-
E_V+0.37	3.7×10^{12}	4.0×10^{12}	4.2×10^{13}	5.2×10^{13}
E_V+0.54	-	-	1.2×10^{12}	-
E_C-0.17	-	-	2.5×10^{12}	1.7×10^{12}
E_C-0.24	1.7×10^{12}	1.9×10^{13}	3.1×10^{13}	2.9×10^{14}

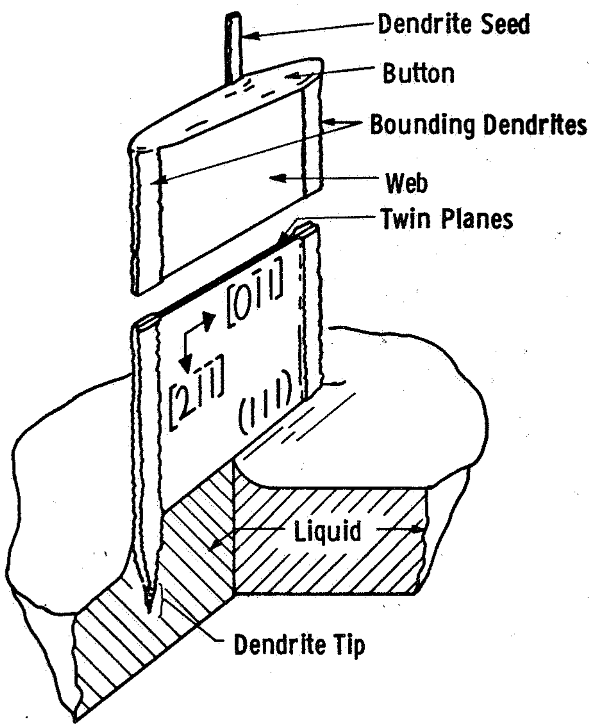

Figure 1: Schematic section of web growth.

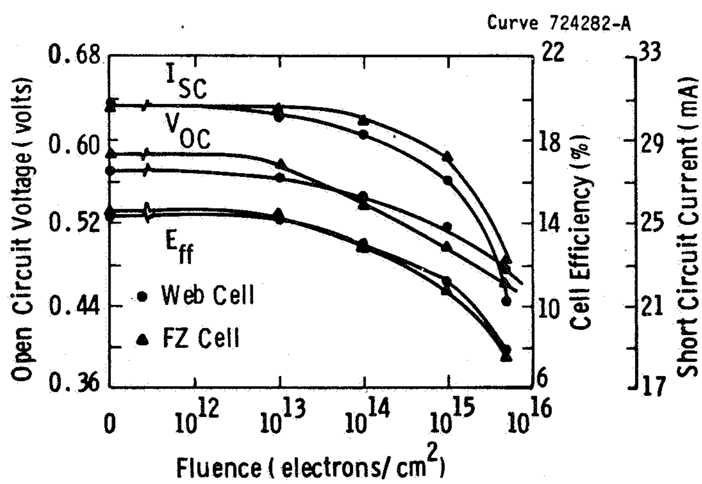

Figure 2: Effect of 1 MeV electron irradiation on float zone silicon and web solar cell.

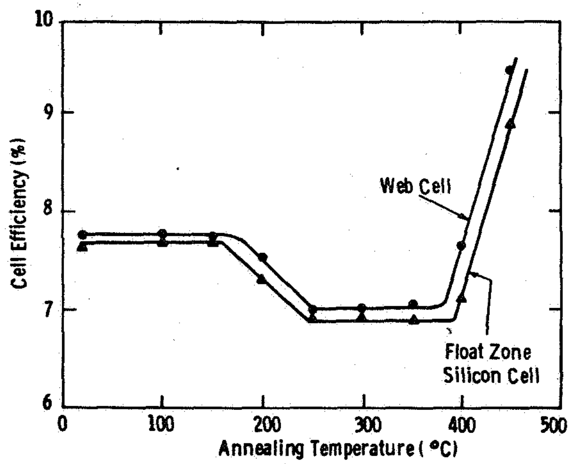

Figure 3: Change in efficiency of electron irradiated ($5x10^{15}$ e/cm^2) cells as a function of isochronal anneal. Efficiencies prior to irradiation were ~14.5%.

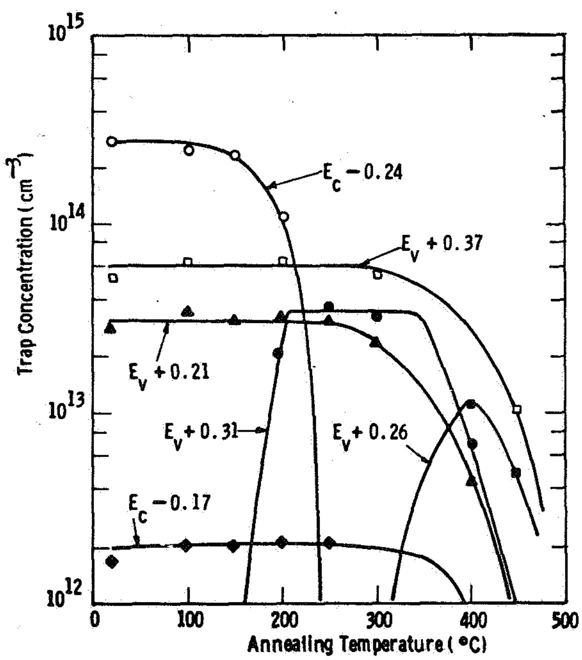

Figure 4: Change in defect concentrations during isochronal anneal of electron irradiated ($5x10^{15}$ e/cm^2) web solar cell.

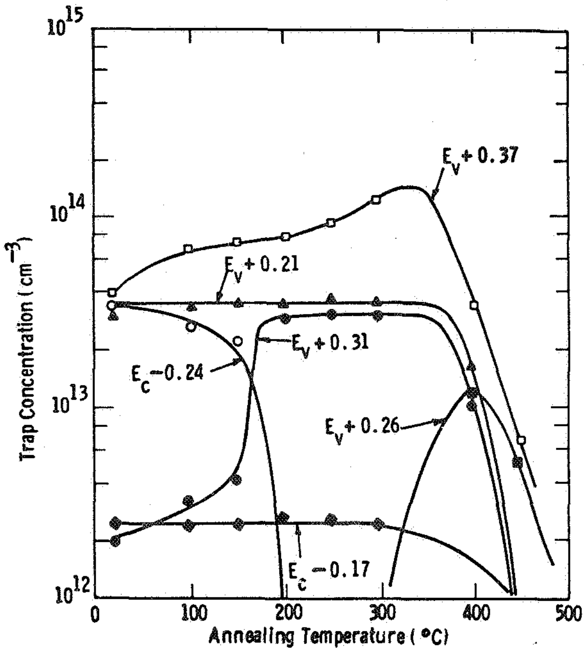

Figure 5: Change in defect concentrations during isochronal anneal of electron irradiated ($5x10^{15}$ e/cm^2) float zone silicon cell.

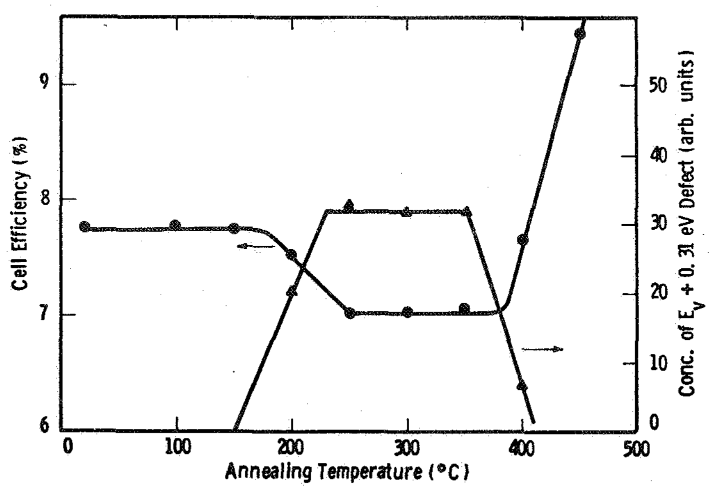

Figure 6: Relationship between the annealing behavior of E_V + 0.31 eV defect and reverse annealing of electron irradiated web solar cell.