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Time and injection rate dependence of minority-carrier diffusion length in solar cells irradiated with x rays

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The minority-electron diffusion length in commercial n^+p silicon solar cells was determined from measurements of transient photocurrent generated by low-energy x rays. The results show an order of magnitude increase in diffusion length over a time interval inversely proportional to the square of the injection rate. This accounts for the occurrence of dose rate sensitivity of silicon detectors of x rays at very low injection rates. The strong rate dependence observed suggests a space-charge trapping mechanism.

Silicon photodiode detectors have been used in high-energy x-ray and electron beam dosimetry at energies above 200 keV, where the mass absorption coefficient is relatively independent of energy.[1] Relative energy independence also occurs in the range 20–40 keV in thin silicon photodiodes.[2] This range is used in scanning for breast cancer in mammography. With high-volume sensitivity, low cost, and planar geometry, solar cells should be useful for low-energy x-ray dosimetry. The sensitivity of solar cells to x rays has been shown to be injection rate independent over several orders of magnitude;[3,4] however, at the very low injection rates associated with mammography the sensitivity becomes injection rate dependent.[5]

To investigate the time and injection rate dependence, the photocurrent generated in commercial polycrystalline and monocrystalline cells exposed to 40 kVp x rays from a conventional three-phase diagnostic x-ray unit was measured as in Fig. 1. After I to V conversion, the voltage proportional to the photocurrent was recorded and displayed by digital oscilloscope. Variable injection rates were obtained by altering the distance between the cell and x-ray source. The exposure rate X was measured with a Pitman 37D air ionization chamber. The mass absorption coefficient of silicon is about seven times that of air in the energy range 20–40 keV.[2] As the energy to produce an electron-hole pair is 3.76 eV in silicon and 33.7 eV in air, the sensitivity of silicon per unit mass is $7\times 33.7/3.76 = 63$ times that of air. Thus at an exposure rate of X $\mathrm{C\,kg^{-1}\,s^{-1}}$ the injection rate of electron hole pairs in silicon (density 2.33×10^3 $\mathrm{kg\,m^{-3}}$) is given by

$$G = (63\times 2.33\times 10^3/1.6\times 10^{-19})X$$
$$= 9.2\times 10^{23} X \ \mathrm{m^{-3}\,s^{-1}}.$$

Figure 2 shows the transient photocurrent I as a function of time and injection rate G for monocrystalline (Arco) and polycrystalline (Solarex) 100-mm-square cells. As 20 keV photons are about 1000 times more penetrating than visible light, the injection rate is nearly uniform throughout the cell. Therefore, provided the diffusion length is significantly less than the layer width W, the photocurrent is given by $I = GAe(L_p + L_n)$, where L_p and L_n are the hole and electron diffusion lengths, respectively. For the n^+p cells used, the width of the n^+ layer is insignificant and $I = GAeL$, where L is taken as the electron diffusion length. As G is measured and A is known, L may be found. From the data in Fig. 2(a) it is found that the diffusion length increases from an initial value $L_0 = 20$ μm to a limit value $L_F = 160$ μm during an interval which is strongly injection rate dependent. Similarly from Fig. 2(b) the diffusion length increases from 20 to 100 μm. The physical widths of the monocrystalline and polycrystalline cells are $W = 450$ and 470 μm, respectively.

In silicon, the diffusion length is determined by the recombination center density N and at low injection levels $L = (D/\sigma v N)^{1/2}$, where D is the diffusion constant, v is the thermal velocity, and σ is the capture cross section for electrons. Thus the observed increase in L may be due to a reduction in recombination center density to some limit value N_F at a rate which depends on the generation rate G. This suggests a variation of recombination center density of the form $N = (N_0 - N_F)\exp(-BG^n t^m/m) + N_F$, where B is a constant related to the capture cross section and n and m are undetermined powers. The corresponding time and rate dependence of the photocurrent is $I = GAeL_F/[(L_F^2/L_0^2 - 1)\exp(-BG^n t^m/m) + 1]^{1/2}$, where the product $GAeL_F = I_F$ is the limit photocurrent.

Plotting $\ln[I_F^2/I^2 - 1]$ vs t^m for each curve in Figs. 2(a) and 2(b) provides a linear fit for $m = 2$ (Fig. 3), and plotting the slope of these curves ($BG^n/2$) vs G^n for each cell provides a linear fit for $n = 2$ (Fig. 4) and a value of B for each cell. Thus an empirical fit to the data in Figs. 2(a) and 2(b) can be obtained with $n = 2$ and $m = 2$ in the equation above and values for the three parameters L_0, L_F, and B. Theoretical curves with $L_0 = 18$ μm, $L_F = 97$ μm, and $B = 2.6\times 10^{-37}$ $\mathrm{m^6\,s^4}$ for the polycrystalline cell, and $L_0 = 18$ μm, $L_F = 160$ μm, and $B = 6.4\times 10^{-37}$ $\mathrm{m^6\,s^4}$

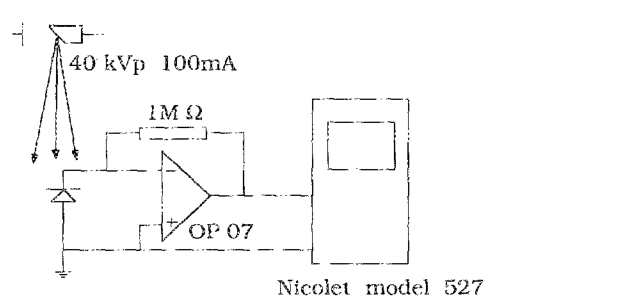

FIG. 1. Photocurrent generated under x-ray irradiation is converted to a voltage and recorded by digital oscilloscope.

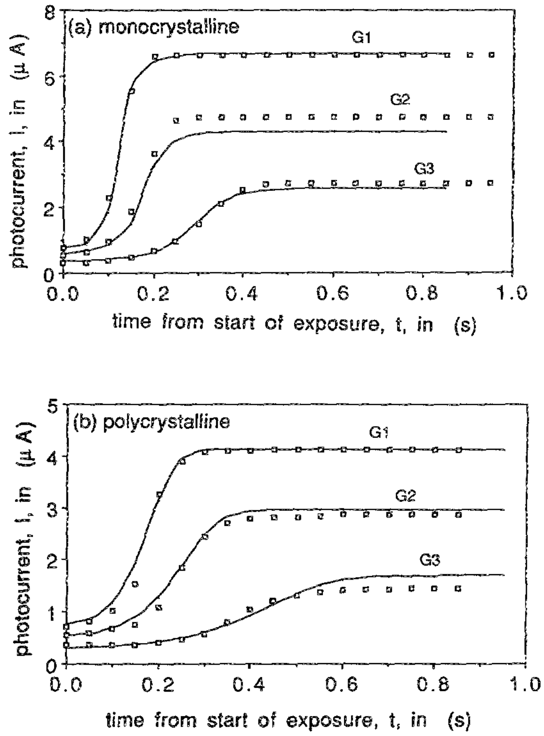

FIG. 2. Measured photocurrent as a function of time and injection rate G for (a) monocrystalline and (b) polycrystalline commercial 100-mm-square cells. ($G1 = 2.7\times10^{19}$ $m^{-3}\,s^{-1}$, $G2 = 1.9\times10^{19}$ $m^{-3}\,s^{-1}$, and $G3 = 1.1\times10^{19}$ $m^{-3}\,s^{-1}$.)

for the monocrystalline cell are shown as the full lines in Figs. 2(a)and 2(b), respectively.

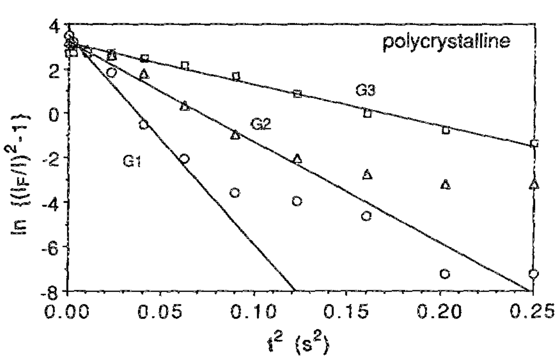

FIG. 3. $\ln[(I_F/I)^2-1]$ vs time squared for each transient of Fig. 2(b). The straight line fits to the initial stages of each curve have been made by eye.

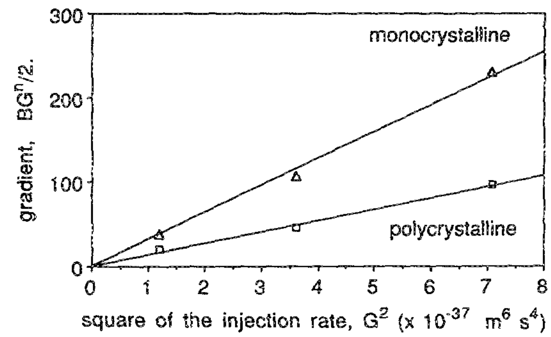

FIG. 4. Exponent factor $BG^n/2$, plotted as a function of G^2 for each cell.

The corresponding rate equation for the decrease in recombination center density is $dN/dt = -BG^2Nt$. It is not clear how this time and rate dependence might arise from the rate equations usually applied to indirect semiconductors,[6] however, the strong rate dependence suggests the minority-carrier density and center density both depend on G, which in turn suggests some form of space-charge trapping[7] may apply.

In summary, the minority-carrier diffusion length in monocrystalline and polycrystalline commercial solar cells was found from measurements of photocurrent generated by low-energy x rays. At very low injection rates the diffusion length increases by about an order of magnitude over a time interval which depends inversely on the square of the injection rate. When the injection rate is low the transition time interval may be a significant proportion of the time of exposure, in which case the silicon detector becomes rate dependent. The strong rate dependence, (G^2), may explain why previous studies[3,4] have not shown the transition.

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