MEASUREMENT OF MINORITY-CARRIER DRIFT MOBILITY IN SOLAR CELLS USING A MODULATED ELECTRON BEAM*

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The hypothesis has been advanced that processing effects on minority-carrier drift mobility may explain variations in open-circuit voltage among space-quality silicon solar cells subjected to different processing protocols.[1] Also, some evidence exists that integrated circuit process flows may result in degradation of drift mobility.[2] It is therefore of interest to determine the mobility or, equivalently, the diffusivity in solar cells, without subjecting them to additional processing steps.

A determination of diffusivity on solar cells is here reported which utilizes a one-dimensional treatment of diffusion under sinusoidal excitation. Cells used were the same as those employed in Ref. 1. An intensity-modulated beam of a scanning electron microscope (SEM) was used as a source of excitation. The beam was injected into the rear of the cell, and the modulated component of the induced terminal current was recovered phase-sensitively. A Faraday cup to measure the modulated component of beam current was mounted next to the sample, and connected to the same electronics, as shown in Figure 1. A step-up transformer and preamplifier were mounted on the sample holder. Beam currents on the order of 400 pA were used in order to minimize effects of high injection. The beam voltage was 34 kV, and the cell bias was kept at 0 V.

The amplitude of the junction terminal current as a function of modulation frequency is presented in Figure 2 for two types of specimens. The ratio of the sample current to measured beam current is shown. Initially, little response was detected as the beam was injected into the back surface. Good results were obtained after a groove was cut into the back surface using a diamond saw. This served to cut through a back surface layer characterized by high recombination velocity. Curves shown are for model calculations to be discussed below. Measurements of phase delay of sample current with respect to Faraday cup current are given in Figure 3 for the same two cells.

Results were analyzed using a one-dimensional treatment of diffusion under sinusoidal excitation, following McKelvey.[3] Low injection conditions were assumed. The continuity equation to be satisfied for excess density $\Delta n(x,t)$ is

$$D \frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{\tau} = \frac{\partial(\Delta n)}{\partial t} ,$$

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where D is the diffusivity and τ the minority-carrier lifetime. The solution for sinusoidal excitation is

$$\Delta n(x,t) = \Delta n(x)\cos(\omega t) = \Delta n(0)\, e^{-\beta x/L} \cos(\omega t - \gamma x/L)$$

for diffusion in the positive x-direction and excitation source at the origin. L is the diffusion length. Here β and γ are given by

$$\beta = \left[\frac{1}{2}\left(1 + \sqrt{1 + \omega^2\tau^2}\right)\right]^{1/2}$$

and

$$\gamma = \left[\frac{1}{2}\left(-1 + \sqrt{1 + \omega^2\tau^2}\right)\right]^{1/2}$$

In the present case, the solar cell junction samples the excess density at some distance $x = R$ from the point of injection. A best fit to the observed amplitude dependence is obtained by varying the diffusion length and the lifetime. (In this manner, an approximate value of diffusivity can be obtained by use of the equation $L^2 = D\tau$.) The best fits are shown in Figure 2, along with fits for other values of L to indicate the sensitivity of the fit to choice of L. Using the best value for L, a fit of the phase dependence (Fig. 3) is obtained by choice of lifetime or, equivalently, diffusivity. An additional fit to the data, obtained using a different value of diffusion length (discussed below), is also shown.

The best value of diffusivity for specimen 672-5 appears to be 17 cm^2/sec, and for 664-1, 14 cm^2/sec. Equivalent mobilities may be determined using the Einstein relationship, $eD = \mu kT$. The calculated mobilities are 660 and 540 cm^2/V-sec, respectively. The base resistivity in these cells is 0.1 ohm-cm,[1] and published values of drift mobility for this resistivity are in the range of 400-440 cm^2/V-sec.[4,5] The present experimental values exceed the reported ones, contrary to expectations on the basis of processing effects. The quality of the theoretical fits suggest that application of a one-dimensional model is legitimate. The magnitude of scatter in the data indicates that diffusivities are obtained to within about 15% precision. Possible sources of systematic error include effects of high injection, and our assumption that excitation occurs at the surface, rather than at finite depth. Effective depth of excitation could be as large as 3 μm for the 25 keV beam used, amounting to $\leq 6\%$ of the effective cell thickness (measured from the bottom of the cut). Effects of high injection were tested for by measurement of phase delay for different degrees of beam defocus. No observable effect on the phase was noted. (By contrast, the amplitude showed a slight ($< 10\%$) decrease upon defocussing.)

The cells measured here had been subjected to an unconventional processing sequence.[1] A long emitter diffusion was followed by etch-back and a secondary emitter diffusion. An increase in open-circuit voltage under illumination conditions yielding identical short-circuit currents (25 mA/cm^2) was observed for long primary diffusion times. A decrease in diffusivity was postulated to explain this result. This supposition was supported by cell measurements which showed that the diffusion lengths in the samples were nearly identical, but that lifetimes differed. Judging from the amplitude dependence shown in Figure 2, it appears that neither the diffusion lengths nor the lifetimes in the two samples are identical. We are reluctant to draw quantitative conclusions from the amplitude data, since the assumption of one-dimensional transport is much more questionable in that case than in the case of the phase measurements. Moreover, effects of rear surface recombination have not been taken into account. Finally, the diffusion lengths measured under ac conditions may be governed by trapping rather than recombination, and would be smaller than those determined under dc conditions. Fortunately, assumptions of diffusion length have only minor influence on the determination of drift mobility on the basis of the phase data. If we assume, for example, that the diffusion lengths are ~250 μm, as determined from cell measurements,[1] the diffusivities calculated are found to be 18 and 15 cm^2/sec for the samples 672-5 and 664-1, respectively, vs. 17 and 14 determined above. It should be noted that the diffusion length which yielded the best fit to the amplitude data of sample 664-1, about 35 μm, also yielded the best fit to the phase data. It was anticipated that sample 664-1, which was subjected to a 4-hour primary diffusion, should exhibit a higher diffusivity than the specimen 672-5, which was subjected to a 41-hour primary diffusion. This has not been confirmed in the present measurements.

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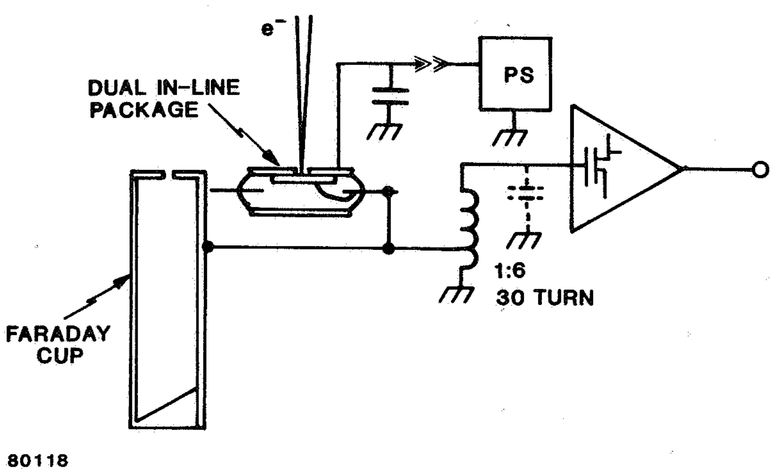

Figure 1. Experimental arrangement for the measurement of cell response in amplitude and phase under conditions of rear-surface injection using a modulated beam.

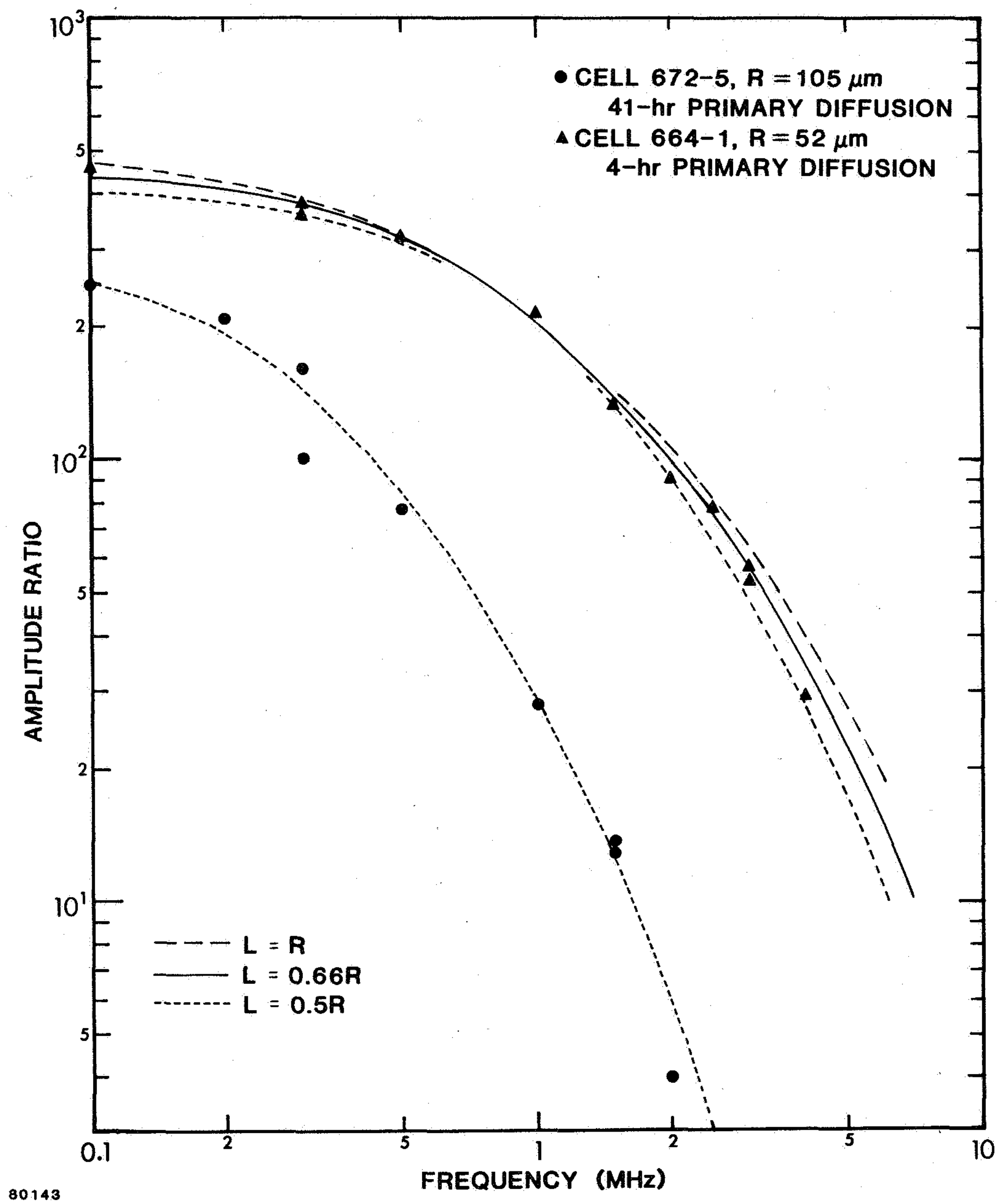

Figure 2. Amplitude ratio of solar cell current to beam current as a function of frequency for two solar cells. Theoretical fits are shown for different assumptions of bulk diffusion length. R is the distance of the point of injection from the junction.

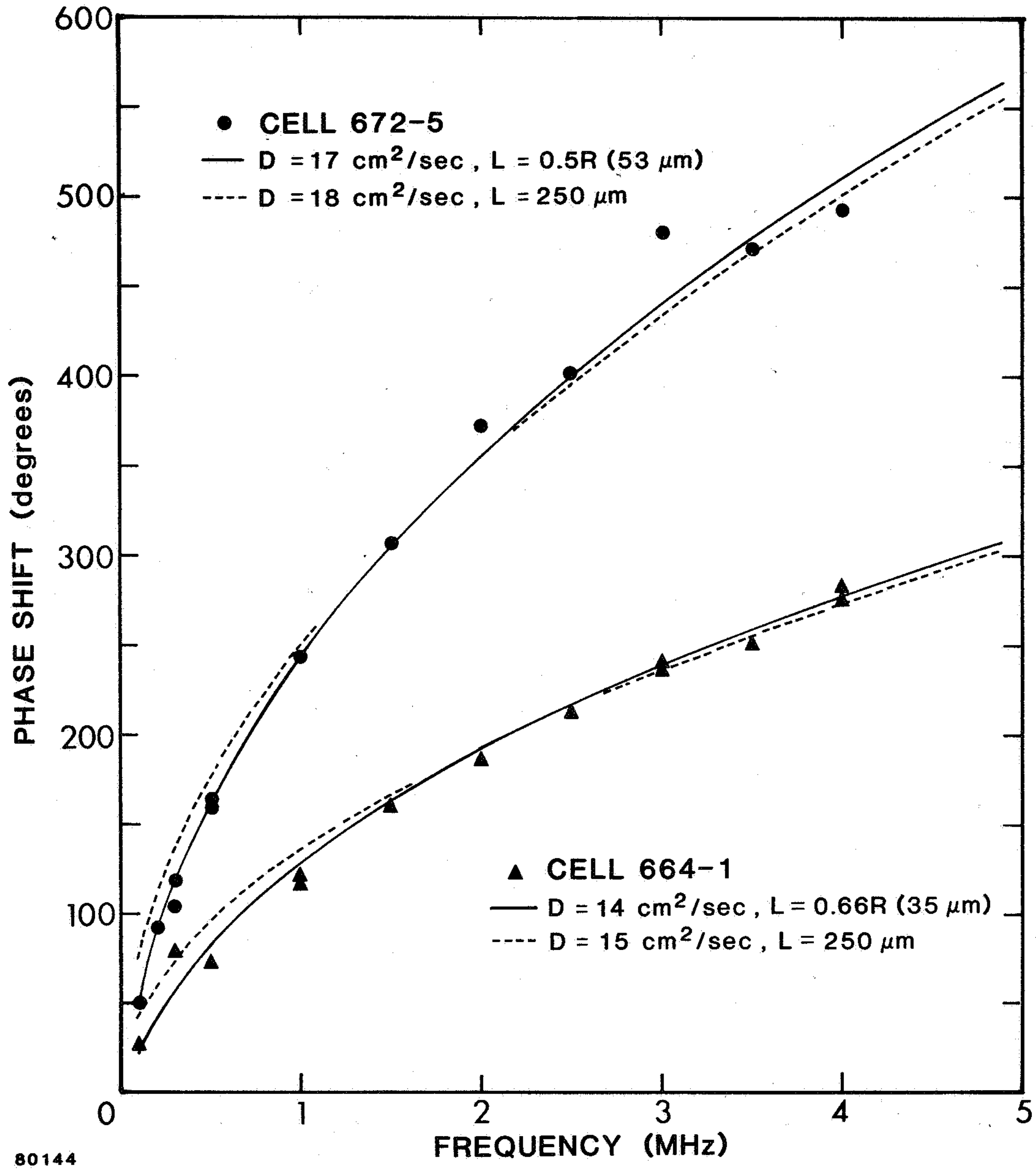

Figure 3. Phase shift of solar cell current with respect to beam current for the two cells treated in Figure 2. Shown is the theoretical fit for the best choice of diffusivity under assumption of diffusion lengths determined from Figure 2, as well as the fit under assumption of 250 μm diffusion length.