DEGRADATION AND RECOVERY MECHANISMS IN LITHIUM-DOPED SOLAR CELLS*

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1. INTRODUCTION

Several large groups of lithium-doped solar cells were received from JPL for radiation hardness evaluation. These cells included some of the most advanced devices produced to date. The evaluations consisted of the determination of the lithium concentrations in the devices and the effect of irradiations with 3×10^{14} and 3×10^{15} e/cm^2 with 1-MeV electrons. In addition some studies were performed using 28-MeV electrons. Capacitance measurements were used to systematically study the changes in lithium concentration which occur during irradiation and recovery.

II. LITHIUM-DOPED SOLAR CELL EVALUATION

During the past year, lithium-doped solar cells from Centralab and Heliotek have been irradiated with 1-MeV electrons and their recovery characteristics have been studied. Several different processing techniques were represented in these cells, including different diffusion gases and varying percentage of lithium coverage of the rear surface. Data for cell groups C11A through C11D, H1A, H2A, H4A, H5A1, H5A2 and H5A3, are listed in Table 1. All of the cells received radiation exposure to 1-MeV electrons. Tungsten I-V characteristics and capacitance versus voltage measurements were then obtained as a function of time at either room temperature or 60°C. The general radiation damage and recovery characteristics of each cell group are summarized in Tables 1 and 2. The recovered levels given in the tables are the

peak of the recovery curve and do not take into account any redegradation that may have occurred. In general, it can be observed that the higher lithium concentrations result in lower initial characteristics, higher recovered levels, and more rapid annealing rates, whereas with lower lithium concentrations, higher initial and slower recovery rates exist. It should be noted that most cell groups tested were superior to the contemporary N/P cells in recovered level. The initial short-circuit current of many of the cells studied was inferior to the contemporary N/P cells.

A. Centralab Cells

The Centralab cells submitted for evaluation were all fabricated from quartz-crucible-grown silicon, with the exception of group C11C. The variable of boron dopant gas was investigated by diffusing the P-type front surface with boron trichloride in the case of group C11A and boron tribromide in the case of group C11B. The short-circuit current values of cells received in group C11B were rather low (53 mA) compared to that group C11A. This difference is not believed to be related to the use of boron tribromide. It is known that when Texas Instruments manufactured solar cells, their P-type diffusions were made with boron tribromide. A second important difference between the cells of these two groups is concentration of lithium found at the junction. Although the cells of both C11A and C11B groups were lithium diffused in the same manner (480 min at 325°C), the data in Table 2 indicates that group

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C11A contains twice the lithium concentration of group C11B. This difference is not considered to be related to use of boron tribromide. The effect of this lower lithium concentration can be seen in the 60°C recovery data in Table 2. The cells of group C11A are nearly fully recovered 200 h after irradiation; however, those of C11B appear to be only half recovered at a comparable recovery time. This slower recovery is probably due to the lower lithium concentration. The recovered I_{sc} values of the C11A group cells are 38 mA after irradiation of 3×10^{15} e/cm^2. The value is significantly better than the comparable data for conventional N/P cells. Recovery in the C11B group has not progressed sufficiently to determine final recovered I_{sc} value.

The cells of group C11D were lithium diffused at the slightly higher temperature of 375°C for 180 min. This diffusion schedule resulted in a higher concentration of lithium at the junction. These cells have about 5×10^{14} lithium atoms/cm^3. The C11A cells diffused at 325°C for 480 min had only 3×10^{14} Li/cm^3. It is also noted that slope of the log capacitance versus log voltage is -0.26. This is the lowest value found in the current group of cell under evaluation. The high lithium concentrations in group C11D are reflected in a slightly more rapid recovery after irradiation. The initial I_{sc} values of the cells in groups C11A and C11D are comparable with those of conventional N/P solar cells. The cells of groups C11A, C11B, and C11D are interesting in that they have the lowest lithium concentrations of any quartz-crucible-silicon cell evaluated by TRW. The relatively poor performance of cells in group C11B indicate that for this type of cell, the concentration of lithium at the junction should be kept above 2×10^{14}/cm^3.

The remaining Centralab group, C11C, was fabricated from Lopex (low oxygen, low dislocation) silicon. In general, the performance of the group was very good. The cells were lithium diffused at 325°C for 480 min. The resulting lithium concentration in this group was 1.5×10^{14}/cm^3. The results of the 3×10^{14} e/cm^2 and 3×10^{15} e/cm^2 radiations are shown in Table 1. In both cases, the I_{sc} recovered to values greater than those of comparably irradiated N/P solar cells, as shown by the dashed lines on these graphs. Although the recovery kinetics are relatively slow in these cells, due to the lower lithium concentration, the irradiated cell performance is among the best received to date.

The cells from the C13 series, manufactured by Centralab, represent a matrix of lithium diffusion temperatures and times. The matrix is designed to investigate the optimum lithium diffusion and the reproducibility of the process. All the cells were fabricated from quartz crucible grown silicon with resistivities between 25 and 40 Ω-cm. The diffusion matrix is shown in Table 2. Also shown in the table are the mean donor concentrations at the junction of the cells of each group in the matrix. The voltage-capacitance relationship or range of relationships is also shown for each group. The donor concentrations were determined by means of capacitance. Since the phosphorus concentration is approximately 1.5×10^{14} atoms/cm^3, the lithium concentrations were estimated by subtracting the phosphorus concentration from the donor concentrations. Since

the phosphorus concentration may go as high as 2×10^{14} atoms/cm^3 (i.e., 25 Ω-cm), some groups may contain cells with very low lithium concentrations. Specifically these are the cells which received diffusions of 6 or 7 h. It can also be observed that both higher temperatures and longer diffusion times result in greater variations in lithium concentration.

It can be seen from the data in Table 2 that, in the time span studied, the lithium concentrations at the junction are decreasing with time. Such a decreasing lithium concentration is inconsistent with diffusion from an infinite source. Since the donor concentration originally was equal to the phosphorus concentration, it was necessary for the donor concentration to rise from the original to a maximum before declining. This decrease in lithium concentration with diffusion time is characteristic of diffusion from a starved source. As the lithium source is exhausted, the surface concentration of the cells will decrease and concentrations at the junction will decrease. In the past, manufacturers of lithium solar cells have interrupted the lithium diffusion and removed the lithium source to produce starved source diffusion. This second diffusion has been referred to as a redistribution. The data in Table 2 indicate that redistribution is not necessary. It is not clear what causes the exhaustion of the lithium source.

Three cells of each C13 series group were irradiated with 3×10^{15} e/cm^2 (1 MeV) and were allowed to recover at 60°C. The most pronounced changes during recovery occur in the short-circuit current. The open-circuit voltages of nearly all cells in the C13 series were about 0.6 V. After a 3×10^{15} e/cm^2 irradiation, the V_{oc} was reduced to about 0.45 V in all cases. Very little recovery is subsequently observed in this parameter. The changes in I_{sc} for cells of the C13 series are shown in Table 2. Several general observations can be made about these cells. With a few exceptions, the 3×10^{15} e/cm^2 irradiation reduced the I_{sc} to 20 to 25 mA. In most cases, the time necessary for the I_{sc} to reach the half recovery point was 100 to 200 h at 60°C. This time is somewhat longer than what was previously found in similar cells. Except for cells with low lithium concentration, most cells ultimately recover to I_{sc} values of 35 to 40 mA. The most important factor in the extent of the recovery is the lithium concentration at the junction rather than the diffusion schedule. As previously noted, the shorter low-temperature diffusions produce the more consistent results. The donor concentration of each cell irradiated is noted in Table 2.

B. Heliotek Cells

All Heliotek cells received for evaluation during the past quarter were fabricated from either floating zone or Lopex silicon and, therefore, had lower oxygen concentrations. There are two different experimental variables represented in these Heliotek cells. Two groups (H1A and H4A) were diffused at lower temperatures: 325°C lithium diffusion for 480 min. Group H2A was lithium diffused at 425°C for 90 min with a 120-min redistribution cycle. This latter diffusion schedule has been used extensively in the past and can be regarded as control. The capacitance measurements results from the H1A group, shown in Table 1, indicate that very little or no lithium

reached the junction. For this reason the irradiation recovery results shown in Table 1 are very poor. Although some recovery is observed after $3 \times 10^{14} e/cm^2$, the higher fluence of 3×10^{15} e/cm^2 exhausts the lithium and no recovery is observed. These results are in direct conflict with those for group H4A which had an identical history. The H4A cells had approximately 5×10^{14} lithium atoms/cm^3 at the junction, and exhibited *satisfactory recovery as shown in* Table 1. The recovered I_{sc} values of the H4A cell would probably have been higher if the before-irradiation I_{sc} values had been higher than 46 mA. This condition is not necessarily a result of the lithium diffusion, as other cells with similar lithium concentrations have initial I_{sc} values in excess of 60 mA. Despite this difficulty, the data indicated that cells of group H4A recover to I_{sc} values of 40 mA after a fluence of $3 \times 10^{15} e/cm^2$. This is considerably higher than a comparable irradiated N/P solar cell.

The irradiation recovery results for the cells of group H2A are shown in Table 1. As mentioned previously, this lithium diffusion schedule has previously been used many times to produce superior lithium cells. The results in Table 1 confirm that such cells exhibit excellent I_{sc} values when recovered from an irradiation. The results in the case of the $3 \times 10^{15} e/cm^2$ fluence are particularly interesting in that the recovered I_{sc} reached a value of 44 mA. The fact that these cells were fabricated from Lopex silicon as opposed to float-zone silicon is not considered significant.

The remaining groups of Heliotek cells represent a series of experiments to determine the effectiveness of area coverage during the application of lithium diffusion source material to the back of the cell. Groups H5A1, H5A2, and H5A3, respectively, received 100, 80, and 50% back surface area coverage. The results of this experiment are very interesting for comparative analysis. The first point of interest is the measured lithium concentrations at the junctions of the various groups as seen in Table 1. The cells with 100% coverage (H5A1) have approximately 6×10^{14} lithium atoms/cm^2 at the junction. The groups which received less coverage (H5A2, H5A3) had roughly half the above lithium concentration. The results indicate quite clearly that decreased area coverage reduces the concentration of lithium at the junction. The relationship does not appear to be linear, since the cells with 80% coverage (H5A2) have lithium concentrations nearly as low as those with 50% (H5A3). It can be concluded that incomplete area coverage with the lithium source material significantly reduces the lithium concentration at the junction. It is also of interest to compare the cells of these groups to cells of other groups. The cells of group H2A were made with the same material and diffusion schedule, but presumably no control on area coverage. The data in Table 1 indicate the H2A cells had much lower lithium concentrations than any of the cells in H5 groups. It must be concluded that there are other unknown factors which extend strong influences on the concentration of lithium reaching the junction. One possible factor could be the chemical activity of the lithium in the source material.

The effects of various lithium source area coverages on radiation response can be seen in Table 1. The initial I_{sc} values of these cells are all relatively low. The values average approximately 51 mA. This parameter influences radiation recovery behavior, because the maximum recovered parameters can only approach and not exceed their initial values. Despite this problem, the cells of group H5A1 (100% coverage) recovered to a maximum I_{sc} of 50 mA after an irradiation of $3 \times 10^{14} e/cm$ and 39 mA after $3 \times 10^{15} e/cm^2$. In both cases these values are above those of similarly irradiated conventional N/P solar cells. The H5A1 cells, irradiated with $3 \times 10^{14} e/cm^2$, show some redegradation of I_{sc} after the maximum was reached. The radiation recovery of cells of group H5A2 (80% coverage) was not drastically altered by the reduced coverage. The cells of group H5A2 which were irradiated with 3×10^{14} e/cm^3 recovered to I_{sc} values of 45 mA. The recovery probably would have exceeded the above value if the initial I_{sc} value had been greater than 46 mA. The $3 \times 10^{15} e/cm^2$ irradiation of H5A2 cell allowed the I_{sc} recovery to 39 mA after irradiation. This value is equal to that achieved in the group having 100% coverage (H5A1). This result is difficult to explain, considering the lower lithium concentration and the studies of D. L. Kendall at Texas Instruments which indicated very little lateral spreading of lithium during diffusion. The results for cells of H5A3 (50% coverage) show comparable performance after $3 \times 10^{14} e/cm^2$ (Table 1). In the case of the higher electron fluence on the H5A3 cell, the recovered I_{sc} values were significantly reduced. It appears that incomplete coverage with diffusion source material does not reduce recovery behavior, except in extreme cases.

III. ELECTRON ENERGY DEPENDENCE OF LITHIUM-DOPED CELL RECOVERY

Most of the studies of radiation behavior of lithium-doped cells have been done with a 1-MeV electron environment. With the exception of a few studies with reactor neutrons and one early study with protons, there is a complete lack of much of the data needed to accurately predict behavior in space. One area in which more data are desirable is response of these cells to electrons with energies greater than 1-MeV. Through the courtesy of Dr. J. A. Naber of Gulf Radiation Technology, several lithium-doped cells were irradiated with 28-MeV electrons.

Because of the necessary delays between the irradiation at the Gulf facilities and analysis at TRW, cells made from quartz-crucible-grown silicon were selected because of their slow recovery rate at room temperature. This allowed the cells to be mailed to TRW before any post-irradiation recovery occurred. The cells used in this experiment were from the C11D series, manufactured by Centralab. These cells are considered to be typical of good lithium-doped cells and adequate 1-MeV electron data had previously been obtained. Cells were irradiated with 3×10^{14} and $3 \times 10^{15} e/cm^2$. The I_{sc} recovered at 60°C to 46 and 31 mA, respectively, for the two fluences. The degraded and recovered I_{sc} values as a function electron fluence are shown in Fig. 1. The previously accumulated 1-MeV data are also shown and typical 1- and 28-MeV data for a 10 Ω-cm N/P solar cell are also shown as dashed lines. The dotted line indicates the I_{sc} value (38 mA) at which the critical fluence has been arbitrarily defined. It has been observed that all solar cells are

degraded by penetrating radiation at a rate of about 6.5 mA/cm² under tungsten illumination for each decade of fluence added. It is apparent that the initially degraded I_{sc} values of the lithium-doped cells decrease at a much smaller rate. In this case, the lower rate is probably due to annealing of defects which occurs during the irradiation. After the 60°C recovery, the I_{sc} of the lithium-doped cells decline 13 mA per decade of fluence. The important point in Fig. 1 is that, while at 1-MeV the lithium cells are slightly superior to the conventional N/P cell, at 28-MeV the lithium cell will withstand over ten times the fluence before being degraded to the same I_{sc} value of a similarly irradiated conventional cell.

IV. LITHIUM-DOPED SOLAR CELL REMOVAL RATE STUDIES

During the past quarter, extensive capacitance studies were made on Heliotek and Centralab cells previously evaluated under 1-MeV electron irradiation. By using techniques previously discussed in reports of this series, the donor concentration in the N-type base can be determined as a function of distance into the base. These studies can be made before irradiation, after irradiation, and after recovery. In this manner the changes in carrier concentration occurring during irradiation and recovery can be determined. These data can be of use in the construction of physical models of the damage and recovery processes and to provide information for the design of improved solar cells. The basic equation used in the analyses is

$$N_d = \frac{SVC^2}{q\epsilon}$$

where

N_d = donor concentration

V = voltage

C = capacitance

q = electronic charge

ϵ = dielectric constant

The factor S is related to the exponent of the $k = VC^n$ relationship for the cell.

A capacitance study was done on Centralab cells from the C11C group. These cells were fabricated from Lopex silicon and showed excellent initial and recovery characteristics. The phosphorus concentration of the silicon was approximately 6×10^{13}/cm³. The before-irradiation data indicate a very much lower donor concentration compared to other cells which have exhibited good recovery. Cell C11C-7 and C11C-3 were irradiated with 3×10^{14} and 3×10^{15}e/cm² electrons, respectively. After recovery from an irradiation of 3×10^{15}e/cm², the donor concentration is approaching the phosphorus concentration. This indicates near exhaustion of lithium donors. The removal rates were calculated for these cells and are plotted in Fig. 2 as a function of barrier width. The removal rates are of interest in this case because of the two different electron fluences used. Although there was some difference in lithium concentration between the two cells, the differences in removal can be considered to be largely

due to differences in fluence. One might expect that the removal rates would be relatively independent of electron fluence, if the behavior is based upon discrete solid-state reactions in which one atomistic species reacts stoichiometrically with another. The fact that during satisfactory recoveries the removal rate has been observed to vary between 1.5 to 4 times that observed during irradiation, indicates that no discrete quantity of lithium appears to react with the radiation products. The data in Fig. 2 indicate that in C11C cells, the removal rates during irradiation and recovery from a 3×10^{14}e/cm² fluence are significantly greater than those resulting from a 3×10^{15}e/cm² fluence. Not only are the removal rates lower with the higher fluence, but the ratio of the rates during recovery and irradiation decrease from 4 to 2 when the fluence is increased from 3×10^{14} to 3×10^{15}e/cm². It is obvious that the models which we have proposed in the past must be modified to account for the widely varying removal rates which we have observed in cells made from low-oxygen silicon.

Our analysis of lithium distributions also included two cells made from silicon grown from quartz crucibles. Our previous studies have shown that the very small removal rate observed during irradiation of this type cell can be explained by the production Si-A centers (oxygen-vacancy pairs) with an introduction rate of about 0.2 cm⁻¹. The two cells (C11A-13, C11D-3) had previously exhibited excellent recovery when irradiated with 3×10^{15}e/cm². The result indicated a very low removal rate during irradiation of both cells. This is because the concentrations of Si-A centers produced are barely detectable in these donor concentrations. Much larger changes in donor concentration occur during the recovery phase. To further study possible relationships, the removal rate data are replotted in Fig. 3 as a function of lithium concentration present at the particular barrier width position after irradiation. In addition similar data from a cell (H14-4921) analyzed during our previous years work are added to Fig. 3.

It can be seen from the data of the three cells shown in Fig. 3 that the removal rate during recovery is directly proportional to the concentration of lithium present at that point in the cell. Since our previous work has shown that Si-A centers are introduced uniformly throughout the active N-type area of the cell, it must be concluded that the amount of lithium which reacts with the radiation produced defects is independent of the concentration of Si-A centers. The earlier proposed models involved the reaction of one or possibly two lithium donor atoms with a Si-A center. It is clear that this model will require considerable modification. It is possible that precipitation rather than ion pairing may be the basis of the recovery reaction. It has already been proposed that the O-V vacancy pair is the nucleation site for the precipitation of lithium in silicon and germanium. In such a process the quantity of lithium donors reacting during recovery would be independent of the number of radiation defects, and the ratio of lithium donors reacting during recovery to the number of radiation defects could vary considerably.

Using previously described capacitance versus voltage methods, the donor concentrations at various distances into the N-type base were determined

before and after irradiation and during the recovery process. The results of such a study of cell C13D-1 are shown in Fig. 4. After 720 h the recovery process, as indicated by the I_{sc} is nearly complete and the changes in donor concentration have diminished. To allow a more systematic study of the lithium donor changes, the data for specific barrier widths were reduced to lithium donor concentration and normalized to that present immediately after an irradiation with 3×10^{15} e/cm^2. These data are shown as a function of time after irradiation, at three different points in the cell, in Fig. 5.

The mathematical form of the change in lithium concentration with time could indicate information regarding the nature of the recovery process. The data in Fig. 5 are plotted in semilog form to detect any relationship between the logarithm of the lithium concentration and the time elapsed. Such relationships may indicate first-order chemical kinetics or some aspects of the precipitation of a second phase. The data in Fig. 5 indicate that the lithium concentration decreases in a nearly straight line form until half of the lithium donors have reacted. The rate of reaction appears to slow to zero as the lithium concentration approaches about 25% of its original value.

It was established earlier that an irradiation of $3 \times 10^{15} e/cm^2$ produced a uniform concentration of defects (probably Si-A centers) of 6×10^{14} cm^{-3} in a lithium-doped cell made from quartz-crucible silicon. Our work has indicated that such an irradiation will cause at least 70% of lithium present to react with the defects. Using cell C13D-1 as an example, this means that near the zero bias position of the N-type side of the space charge region (2 μm) about $6 \times 10^{14} cm^{-3}$ lithium donors react during the recovery. This amounts to a one-to-one relation between defects and reacting lithium donors. At a distance of 3 μm deeper in the N-type region, about $3 \times 10^{15} cm^{-3}$ lithium donors react during recovery. At this point, the concentration of lithium donors reacting during the recovery period is five times that of the radiation defects detected. It would be highly desirable to extend these measurements to deeper areas of the N-type base. After the $3 \times 10^{15} e/cm^2$ irradiation of cell C13D-1, the measured diffusion length of the cell was 4.3 μm. The data in Fig. 4 indicate that immediately after the irradiation, the capacitance-voltage measurement investigates the lithium concentration of the entire active portion of the N-type base. During the recovery phase, the measured diffusion length increased to 17.5 μm. The distance is currently beyond the limits of the capacitance technique. If the original concentration of donors found before irradiation is extrapolated to 17.5 μm, about $2 \times 10^{16} cm^{-3}$ lithium donors are present. If 75% of these react during recovery phase, 50 lithium donor ion cores react for each radiation defect detected. Such behavior is clearly beyond explanation by models previously proposed. A model involving the nucleation of lithium precipitation by the radiation defects appears to be the only one consistent with observed results.

V. CONCLUSIONS

Several groups of lithium-doped solar cells have been evaluated under 1-MeV electron irradiation. Many of these groups indicated superior electrical output after irradiation and recovery as compared to similarly irradiated N/P solar cells. The superior cells are those with lithium concentrations of 2 to 5×10^{14} atoms/cm^3 at the junction. An irradiation of lithium-doped cells with 28-MeV electrons indicated a tenfold advantage of lithium-doped cell over N/P cells. Studies of the changes in the lithium concentration during recovery have shown the amounts of lithium reacting is highly nonlinear in regard to the electron fluence and varies greatly with distance from the junction. The results indicate that precipitation of lithium on radiation defects may be the cause of recovery rather than ion pairing.

Table 1. Float-zone silicon cell recovery characteristics

Cell group	Diffusion schedule (°C/min/min)	N_{Li}, cm^{-3}	Average C versus V slope	1-MeV electron fluence, e/cm^2	Initial level I_{sc}, mA	Damaged level I_{sc}, mA	Recovered level I_{sc}, mA
C11C	325/480/0	1.1×10^{14}	-0.37	3×10^{14}	60.3	34	54
H1A	325/480/0	0	-0.47	3×10^{14}	58	33	45
H2A	425/90/120	0.4×10^{14}	-0.32	3×10^{14}	51	31	48
H4A	325/480/0	4.9×10^{14}	-0.35	3×10^{14}	47	27	46
H5A1	425/90/120	4.2×10^{14}	-0.34	3×10^{14}	52.5	27	50
H5A2	425/90/120	2.8×10^{14}	-0.34	3×10^{14}	46.5	27	45.5
H5A3	425/90/120	2.3×10^{14}	-0.36	3×10^{14}	52.0	27	47
C11C	325/480/0	1.9×10^{14}	-0.34	3×10^{15}	58.5	24.3	39
H1A	325/480/0	0	-0.47	3×10^{15}	56	24	25
H2A	425/90/120	2.7×10^{14}	-0.30	3×10^{15}	56	22	44
H4A	325/480/0	5.6×10^{14}	-0.33	3×10^{15}	46	19.5	40
H5A1	425/90/120	8.5×10^{14}	-0.32	3×10^{15}	47.5	17.2	39
H5A2	425/90/120	4.4×10^{14}	-0.35	3×10^{15}	51	19	39
H5A3	425/90/120	3.8×10^{14}	-0.36	3×10^{15}	53	18	33

Table 2. Crucible lithium solar cell recovery characteristics, 60°C recovery

| Cell group	Diffusion schedule, °C/h	N_{Li}, cm^{-3}	Average C versus V slope	1-MeV Electron fluence, e/cm^2	Initial level I_{sc}, mA	Damaged level I_{sc}, mA	Recovered level I_{sc}, mA
C11A	325/8	3.1×10^{14}	-0.28	3×10^{15}	64.2	22.0	>37
C11B	325/8	1.5×10^{14}	-0.32	3×10^{15}	53.3	24.9	>27
C11D	375/3	5.1×10^{14}	-0.26	3×10^{15}	61.5	20.7	>36
C13A	330/4	2.5×10^{14}	-0.29	3×10^{15}	64.5	22.5	39.0
				3×10^{14}	64.0	33.8	53.0
C13B	330/6	1.6×10^{14}	-0.29	3×10^{15}	61.8	22.7	37.0
				3×10^{14}	61.8	35.7	51.8
C13C	340/3	2.3×10^{14}	-0.28	3×10^{15}	64.0	21.4	39.4
				3×10^{14}	62.5	30.0	50.2
C13D	340/7	2.1×10^{14}	-0.29	3×10^{15}	63.8	22.5	37.8
				3×10^{14}	65.0	35.8	50.5
C13E	350/5	3.1×10^{14}	-0.28	3×10^{15}	64.2	24.5	35.0
				3×10^{14}	59.0	30.1	47.2
C13F	350/5	4.8×10^{14}	-0.28	3×10^{15}	61.5	22.0	36.0
				3×10^{14}	59.8	29.8	49.0
C13G	360/3	6.5×10^{14}	-0.26	3×10^{15}	57.0	19.5	36.5
				3×10^{14}	61.5	29.5	48.0
C13H	360/7	3.7×10^{14}	-0.31	3×10^{15}	63.5	26.0	35.0
				3×10^{14}	61.5	30.0	49.0
C13I	370/4	5.8×10^{14}	-0.29	3×10^{15}	61.0	23.0	35.0
				3×10^{14}	58.0	30.5	47.8
C13J	370/6	3.0×10^{14}	-0.31	3×10^{15}	60.5	24.0	34.0
				3×10^{14}	62.8	37.8	47.0
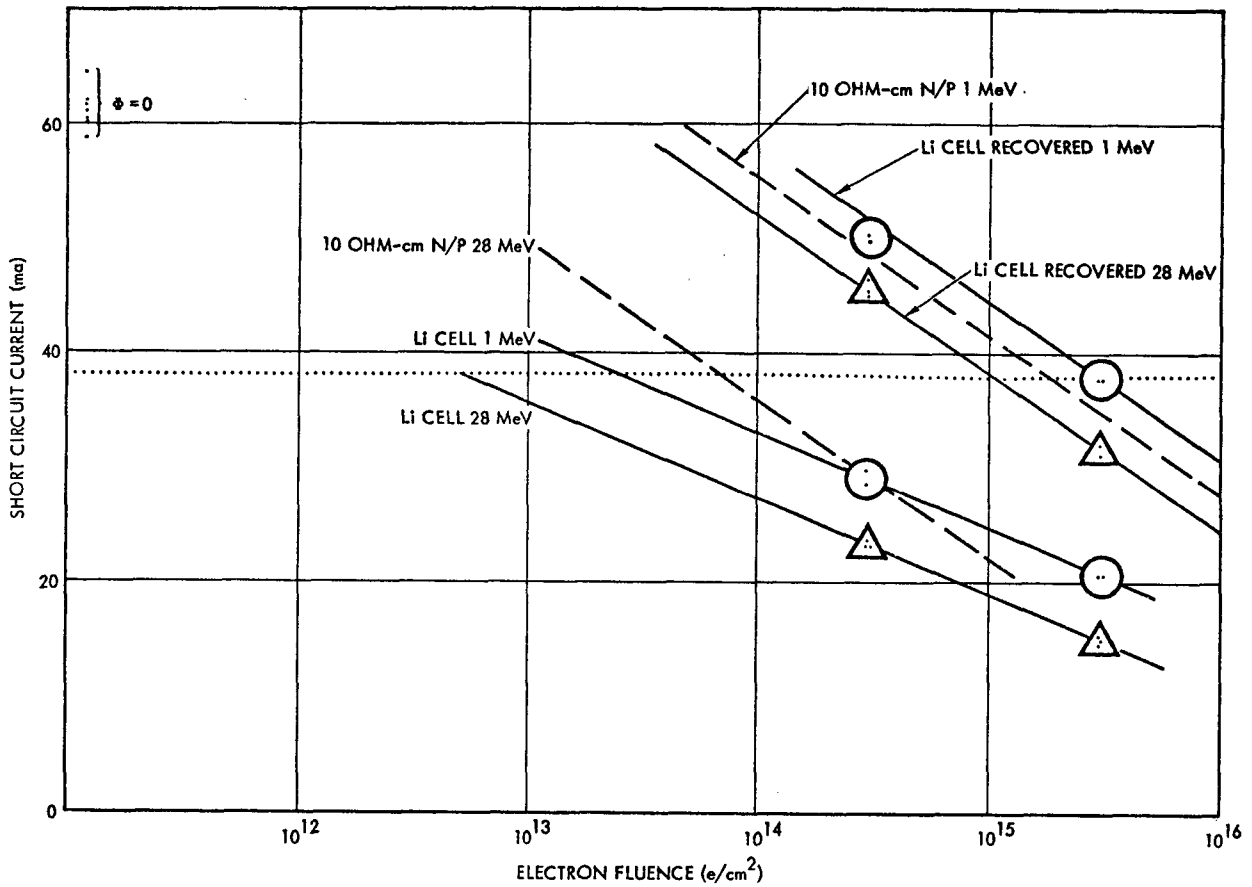
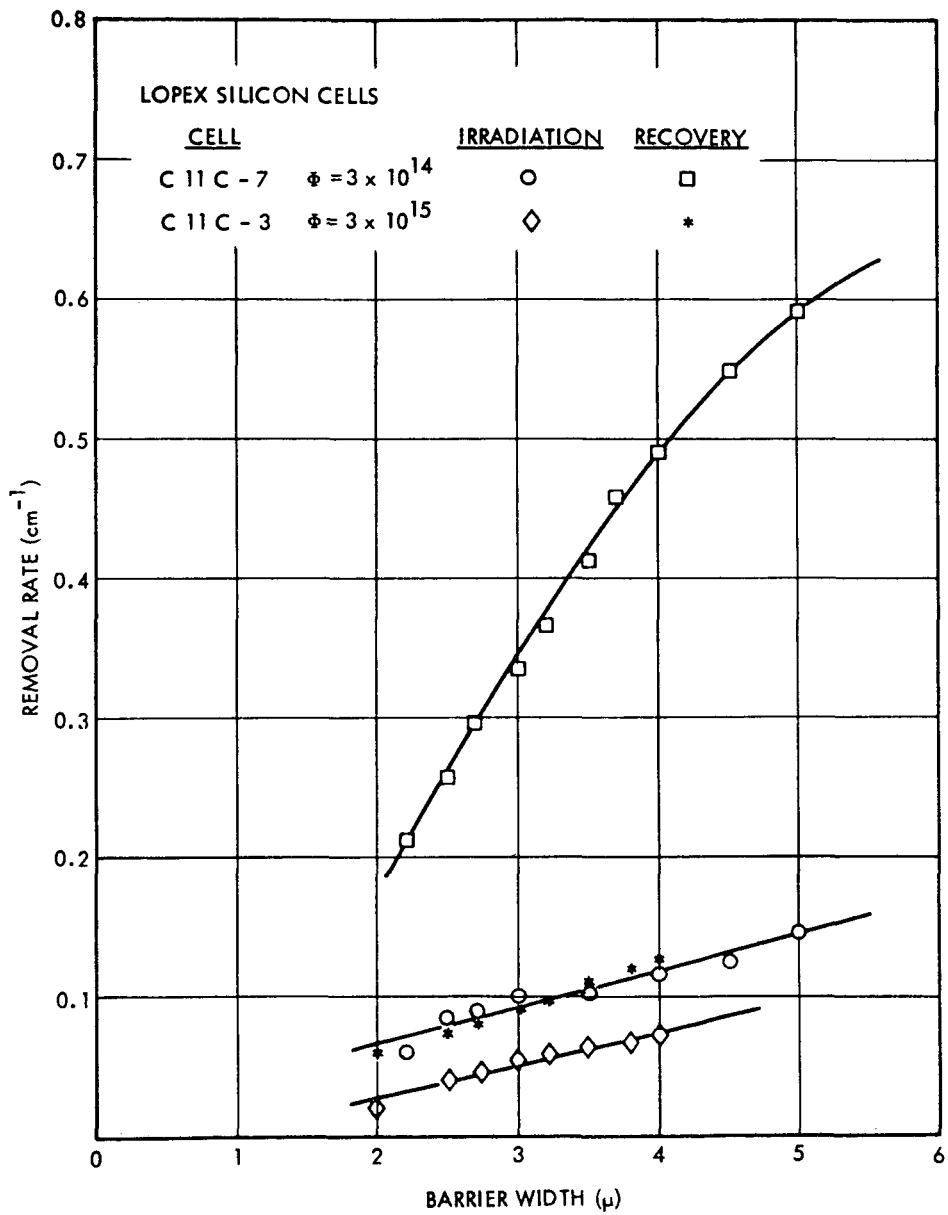Fig. 1. Short-circuit current versus electron fluence

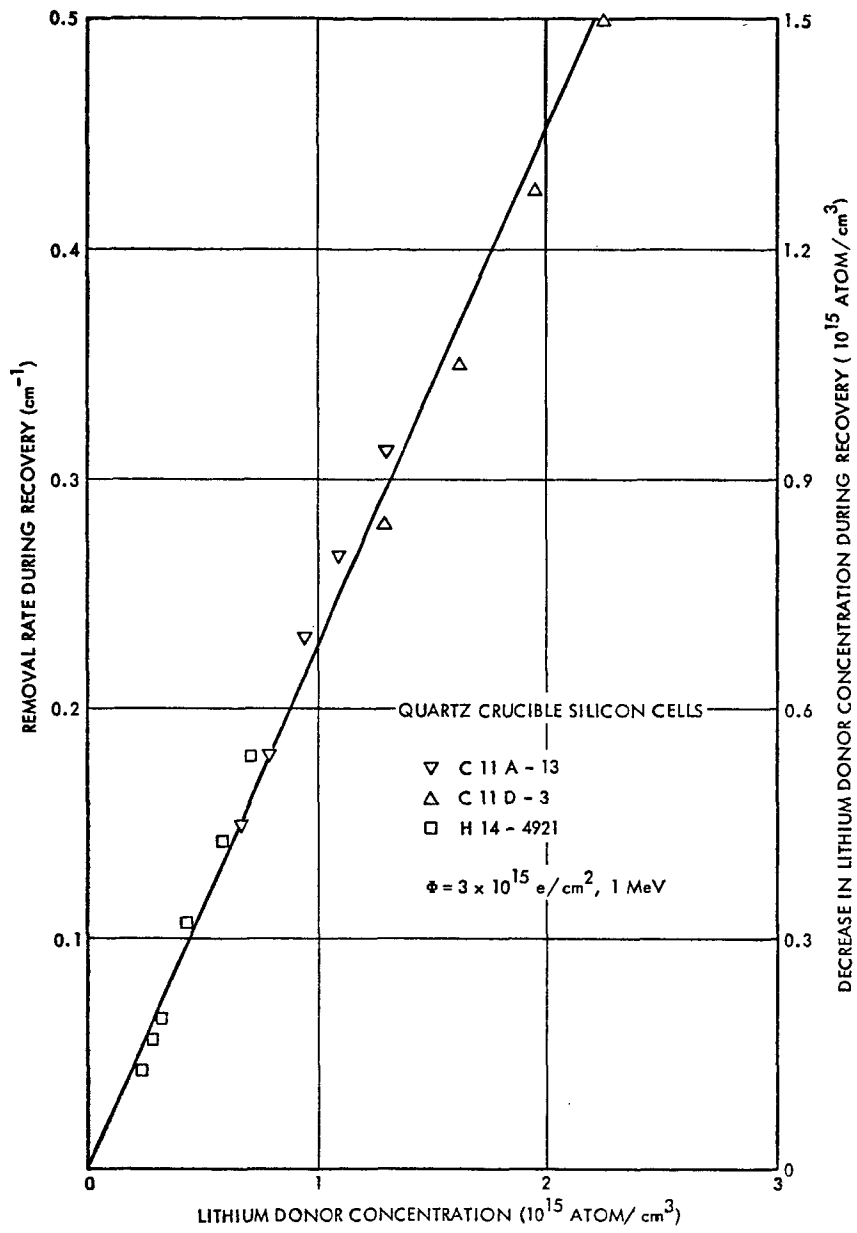Fig. 2. Removal rates of cells of C11C group

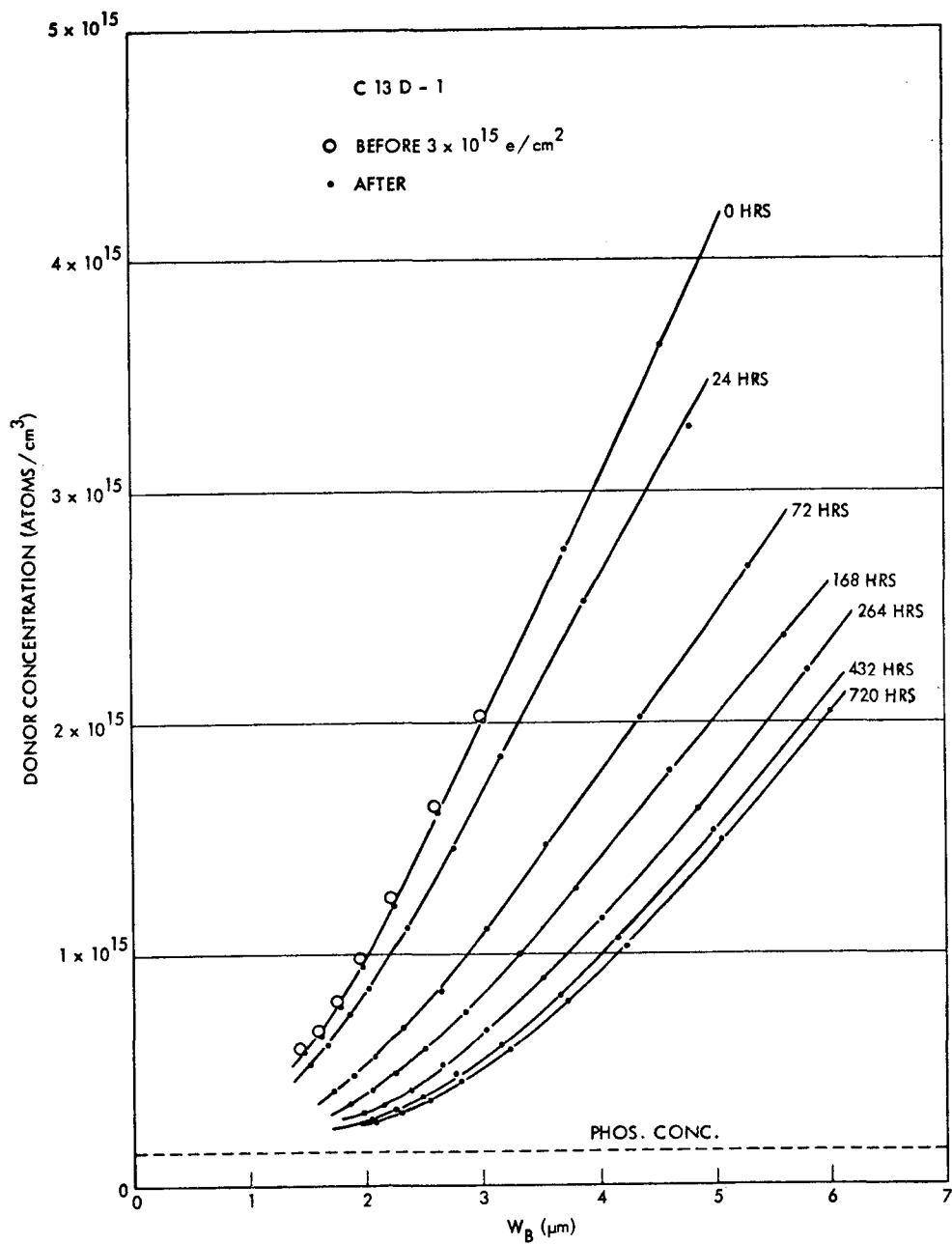Fig. 3. Removal rate versus lithium donor concentration

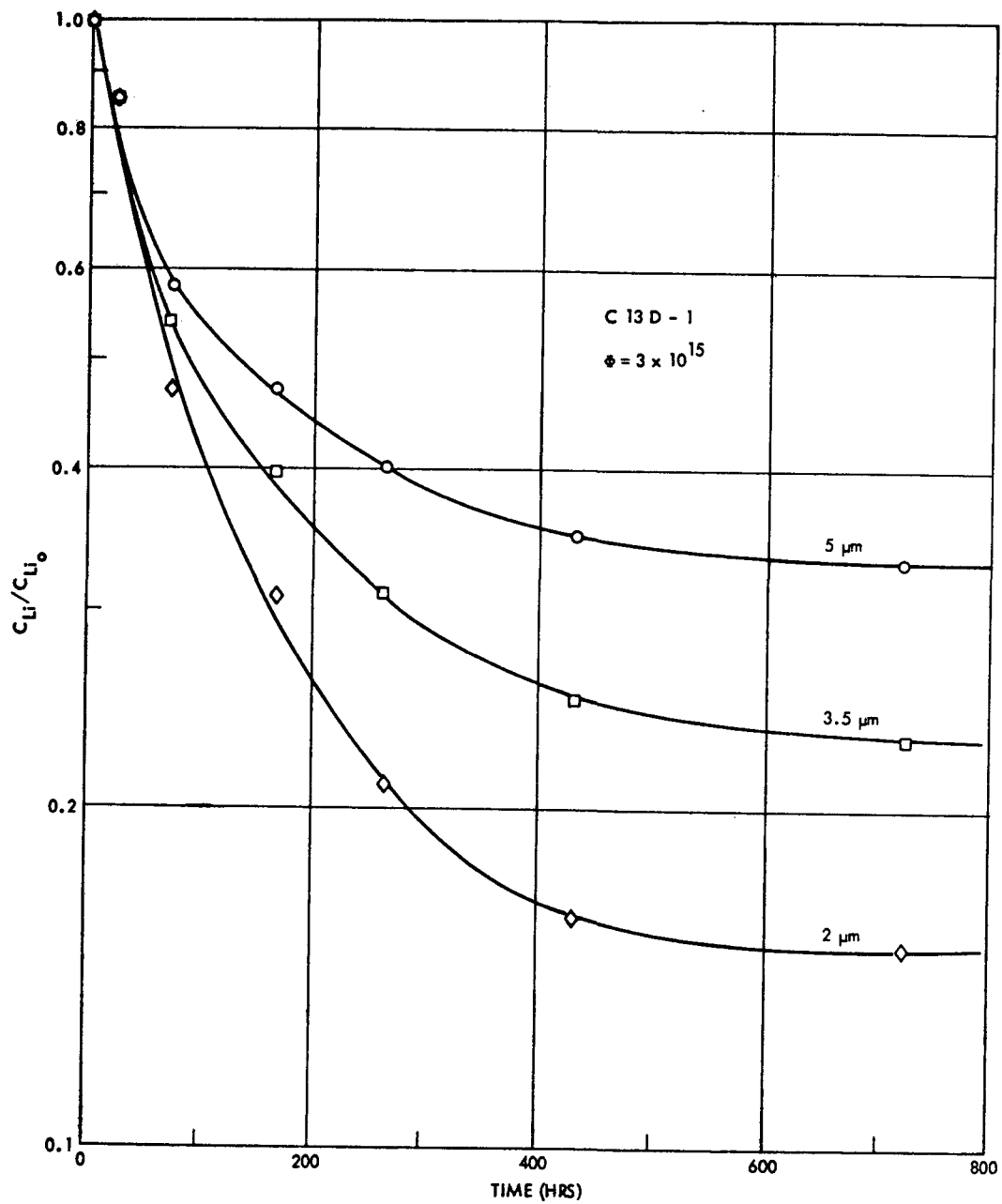Fig. 4. Donor concentration during recovery, C13D-1 cell

Fig. 5. Change in lithium donor concentration during recovery, C13D-1 cell