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Author

Hubbard, G.S.

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Lawrence Berkeley Labo

UNIVERSITY OF CALIFORNIA, BERK

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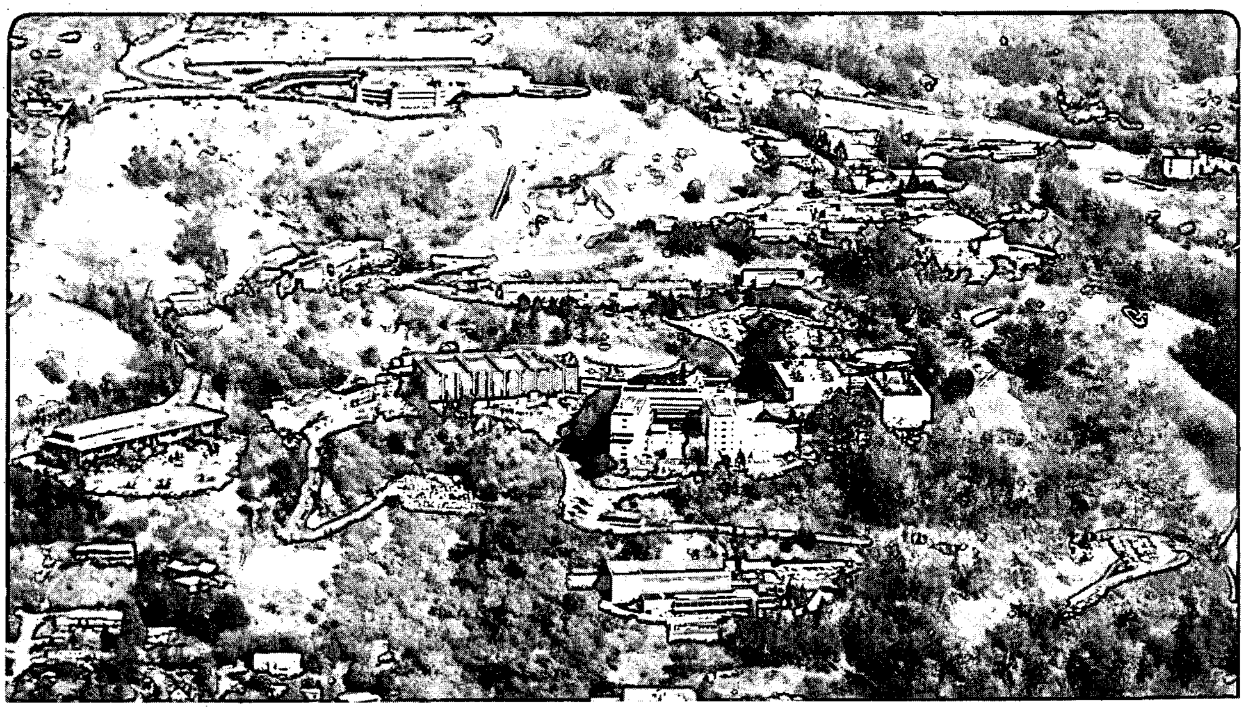

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THE INFLUENCE OF MATERIAL PARAMETERS ON FAST NEUTRON RADIATION DAMAGE OF HIGH PURITY GERMANIUM DETECTORS*

G. Scott Hubbard and Eugene E. Haller

ABSTRACT

High-purity germanium detectors containing differing concentrations of $[H_2]$, [Si] and $[O_2]$ have been irradiated with fast neutrons from a ^{238}Pu ^{9}Be source (average energy 4.2 MeV). Measurements of the full width at half maximum (FWHM) resolution of the 1.17 MeV ^{60}Co photopeak have been carried out as a function of neutron flux, electric field, time after application of bias and detector thickness.

INTRODUCTION

Fast neutrons incident on germanium radiation detectors create radiation damage which causes charge-trapping and a corresponding degradation in detector energy resolution.[1] The large number of parameters which affect the magnitude of degradation (e.g., neutron dose, detector bias, detector size, temperature of detector etc.) greatly complicates the study of neutron induced lattice defects in germanium detectors. For example, previous experiments have indicated that there may be considerable variability in the neutron damage resistance of high-purity germanium radiation detectors.[2] At that time it was suggested that these differences may depend on an undetermined material parameter.

In this work, we present the neutron damage characteristics of seven high-purity germanium planar detectors as a function of various non-electrically active impurities, electric field in the detector, detector thickness and time after irradiation with and without bias. We believe the results of this work will enable one to use high-purity germanium radiation detectors to study neutron induced radiation damage in a more quantitative way than previously possible.

EXPERIMENTAL TECHNIQUES

A total of seven planar, high-purity germanium detectors, 3 cm in diameter, were fabricated, each with a Li-diffused n^+-contact and a ^{11}B-implanted p^+-contact. These devices were selected to represent the widest possible range of material parameters available to us which still allowed a 5 mm detector to deplete at less than a few thousand volts. These detectors and their characteristics are described in Table 1.

To test the effects of neutron irradiation on energy resolution, the FWHM of the 1.17 MeV ^{60}Co γ-ray photopeak was measured as a function of neutron flux. The ^{60}Co source strength was 32 μCi and collection times were ~ 10 mins. All spectra were taken with an electronic peaking time of 4 μs.

A ^{238}Pu^{9}Be neutron source with $Q = 7.6 \times 10^7$ neutrons sec^{-1} was used to irradiate the devices. The average energy of the neutrons from such a source is about 4.2 MeV, although intensity maxima occur at 4.0, 7.2 and 9.7 MeV.[3] Since the experiments were differential in the sense that a number of devices were being examined under equal conditions, the lack of a monoenergetic source was not deemed crucial. Each experiment was carried out with the same cryostat and source detector geometry. Aluminum disks of the same size as our detectors were activated using the ^{27}Al (n, α) ^{24}Na threshold reaction to determine the actual radiation dose in the source-detector geometry used.

Unless otherwise noted the detector temperature during all irradiations and subsequent measurements was ~80 K.

DATA ANALYSIS

While it is extremely difficult to directly relate the FWHM of the ^{60}Co line to radiation induced defects, this measurement is nevertheless one of great practical importance. However, much care must be exercised in comparing different detectors. In order to compare devices which had variations in leakage current and capacitance and hence differing electronic noise contributions, we defined a reduced full width half maximum (RFWHM) of the ^{60}Co photopeak:

$$\text{RFWHM (keV)} = \sqrt{\text{FWHM}^2\ (\text{keV})^2 - \text{NOISE}^2\ (\text{keV})^2}$$

"Noise" = FWHM of electronic test peak.

We shall use this expression consistently throughout this paper.

There are a number of other problems associated with comparing the radiation damage characteristics of various detectors. One of the problems is that the RFWHM of a damaged detector changes as a function of the time bias is applied to the device. The direction of the change depends on the typeness of the germanium. RFWHM of p-type detectors increases with time while the RFWHM of n-type detectors decreases to an equilibrium value. An explanation of these transients has been put forward by Darken et al[9] in which the change in resolution is shown to be consistent with the change in charge state of a deep acceptor. For purposes of comparison, the RFWHM of all p-type devices was measured directly after neutron irradiation and application of bias. As noted later, the sole n-type detector was compared with the p-type devices only after many hours with bias on. In that way the deep traps reached a charge state equivalent to that of a p-type device which had just been biased.

In an unbiased p-type device the deep acceptors are all neutral (i.e., no electron is captured). After depleting the device, the deep acceptors charge up slowly since electrons occasionally get sufficient thermal energy to jump from the top of the valence band into the acceptor level. The charged acceptors then become very effective hole traps, as evidenced by the degradation in RFWHM with time.

Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, U.S.A.

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In an unbiased n-type device, the deep acceptors are negatively charged and slowly become neutral by thermal emission after depletion. Therefore, a radiation damaged n-type detector will show severe trapping immediately after application of bias but will improve toward an equilibrium state with time.

Since the establishment of the final charge state equilibrium depends on the availability of free charges in the depletion layer, the time to achieve the final equilibrium and the actual equilibrium charge state both also depend on the strength of the radiation source used for the spectral measurements. Therefore, the act of measuring the RFWHM influences the final value one gets--much as the uncertainty principle operates in quantum mechanical measurements. As a practical matter then, measurements of any radiation damaged device can only be meaningful when the changes of RFWHM with time and source are considered. To compare p and n-type devices one has to measure p-type detectors immediately after application of bias and n-type detectors after a 'sufficiently' long time with bias on.

RESULTS AND DISCUSSION

Electric Field

In order to fairly compare the data from devices having widely varying depletion voltages, a measurement of detector resolution as a function of average electric field was taken for each device after the neutron irradiation. A typical result is shown in Fig. 1. The RFWHM was found to reach a minimum at or above an average electric field of ~ 1000 Vcm^{-1}.

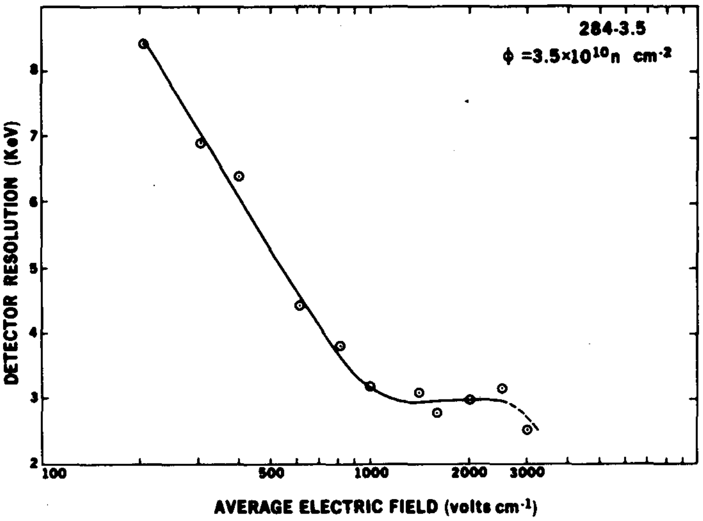

Fig. 1 RFWHM plotted as a function of average electric field for a typical device. The resolution reaches a minimum at or above an electric field of 1000 Vcm^{-1}. Further improvement of RFWHM at higher fields (> 3000 Vcm^{-1}) may be due to field-assisted detrapping.

This finding has been repeated in all devices tested and may be explained by the fact that the saturation velocity of electrons and holes is achieved at a field of ~ 1000 Vcm^{-1}.[4,5] A carrier moving at the saturation velocity would spend the minimum possible time in a given detector volume and thus have the lowest probability of being trapped. One can therefore compare the effects of neutron radiation damage upon the resolution of various devices only if the electric field is ~ 1000 Vcm^{-1} throughout the volume of the detectors. As seen in Fig. 1, the resolution difference between depletion (200 Vcm^{-1}) and high field (1000 Vcm^{-1}) for detector 284-3.5 was more than a factor of two. This result strongly suggests that the wide variability in damage threshold observed in the earlier study by Kraner et al[2] may have been due in large part to the differences in electric field among various detectors.

Material Parameters

Previous evidence has suggested that neither shallow electrically active impurities nor dislocations played any role in the neutron damage behavior of high-purity germanium detectors.[8] Consequently, the present study was carried out using detectors selected to contain different amounts of non-electrically active impurities (H_2,O_2,Si). These impurities are known to form complexes that are carrier trapping centers in high-purity germanium. Two examples are the divacancy-hydrogen center in dislocation free germanium[6] and the silicon-oxygen defect which gives rise to so-called "smooth pits".[7]

As a comparison, "standard" devices were defined as those made from a crystal grown under the usual conditions of high-purity germanium production, i.e., a synthetic quartz crucible containing the melt and an atmosphere of pure hydrogen. Under those conditions we expect [Si] 10^{14}-10^{15} cm^{-3}, [H_2] $\approx 10^{13}$ cm^{-3} and [O_2] ~ 6 x 10^{13} cm^{-3}*. Different amounts of these impurities were prodeced by doping or growing the crystal under very different circumstances (see Table 1). We estimate the range of impurities investigated to be [Si] 10^{14}-10^{17} cm^{-3}, [O_2] 5 x 10^{12} -2 x 10^{14} cm^{-3} and "zero" [H_2] (crystal grown in N_2) to [H_2] 10^{13} cm^{-3}.

Bias was applied and the RFWHM was measured after each neutron irradiation (usually within 15-30 min). The spectra were always taken with highest bias first. The results of irradiating these detectors are shown in Fig. 2. There are no large differences among the various p-type devices tested. Most devices exhibited a RFWHM of ~ 3 keV at a neutron dose of 3.5 x 10^{10} cm^{-2}. The only exceptions were 497-6.8 A (annealed 400 h at 400°C in Bi-Pb) and 508-6.0 (grown in N_2). Both devices required about 40 greater neutron dose before degrading to 3 keV. The reasons for this modest improvement in radiation resistance are not yet clear although one might infer that hydrogen (or its absence) plays a role. The n-type device (612-9.6), grown under an atmosphere of deuterium, was also irradiated and measured as a function of time with bias on. We found that the RFWHM ultimately improved (> 7 hours) to the point expected for a p-type device. Consequently, we do not believe that deuterium has any greater influence on neutron damage characteristics than any other material parameter.

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*The O_2 concentration has been determined by the Li-precipitation method,[12] Si concentration by spark-source mass spectrometry,[13] and the H_2 concentration has been deduced from observations of electrically active impurity-hydrogen complexes.

Resolution Transients

As indicated earlier, the RFWHM of the n-type planar device was observed to improve with time. This behavior is shown in Fig. 3. We observed two regimes, a fast transient with a duration of ~ 20 min and a much slower change lasting over a period of seven hours. Turning off the bias for 10 min. caused the RFWHM to return to the value present after application of bias.

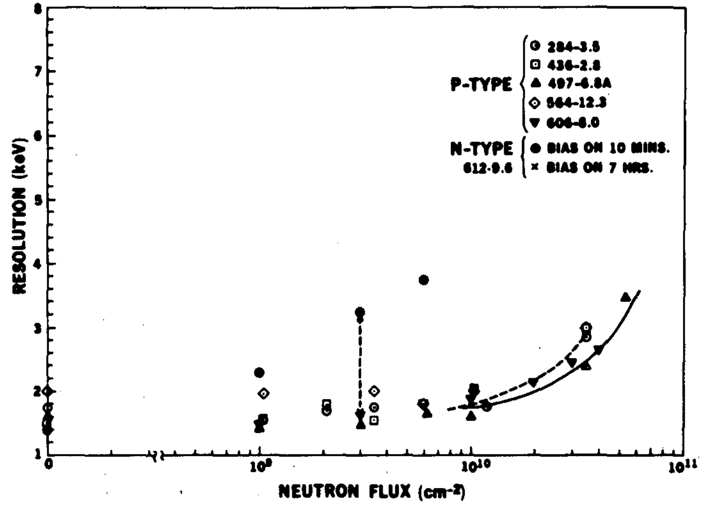

Fig. 2. RFWHM plotted as a function of neutron flux for detectors with different material parameters (see Table 1).

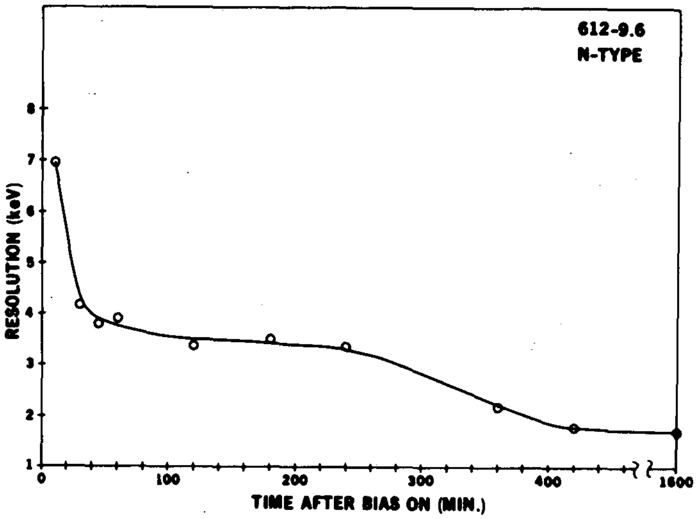

Fig. 3. RFWHM of an n-type planar device plotted as a function of time with bias on (-1200 V). At least two transient regimes are visible. The solid line represents a rough fit to the data.

Figure 4 demonstrates the transient for p-type devices. The resolution of the device has not reached saturation value even at 2800 min. with bias on. However, if the ^{60}Co source is exposed to the detector for times greater than those needed for data accumulation (i.e., ~ 10 min.) the RFWHM begins to improve. A 20 min. exposure was sufficient to change the RFWHM from 10 keV to 8 keV in one case. Leaving the ^{60}Co source on for times of ~ 60 min. reduces the RFWHM to a saturation value of ~ 4.3 keV in this instance. As with the n-type device, removing the bias for a few minutes has the effect of returning the RFWHM to the value just after application of bias.

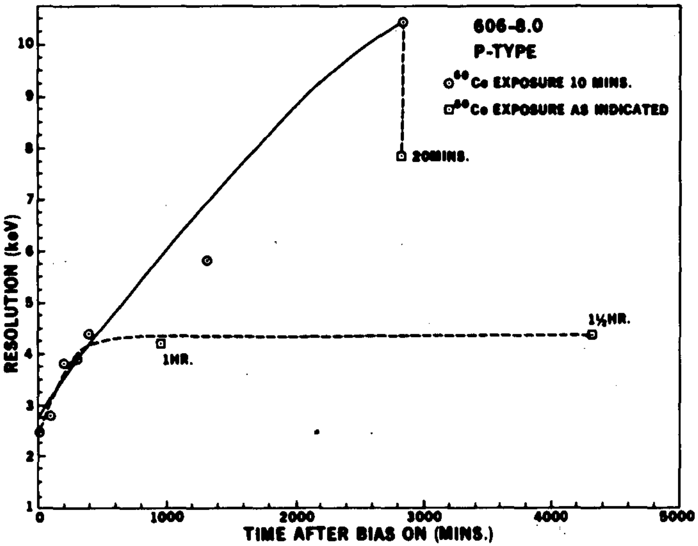

Fig. 4. RFWHM of a p-type planar device plotted as a function of time with bias on (-1100 V). Note the improvement in resolution when the device is irradiated with a ^{60}Co source (indicated by the dashed line).

All irradiated devices were also tested before and after an overnight (~ 16 h) quiescent period. No detector showed any substantial changes except for the device doped with silicon (436-2.8). Overnight the RFWHM increased ~40% from 3 keV to 4.2 keV. We speculate that new acceptor traps may have formed during this period from the movement or rearrangement of impurity-vacancy complexes.

Detector Thickness

Two adjacent devices were prepared from the same "standard" crystal (284), one 0.5 cm thick and one 1 cm thick. Each was irradiated and tested in the same fashion and the applied bias was such that the electric field was $\geq$ 1000 Vcm^{-1} in the whole detector volume. Figure 5 shows the results of this experiment. The thicker detector shows the effects of neutron damage earlier as one might expect. A carrier traveling a larger path length has a higher probability of being trapped. At a dose of 3 x 10^{10} neutrons cm^{-2} we compared the RFWHM of the two devices. After quadratically subtracting the baseline of 1.6 keV the thick device was ~50% worse in resolution than the thin one.

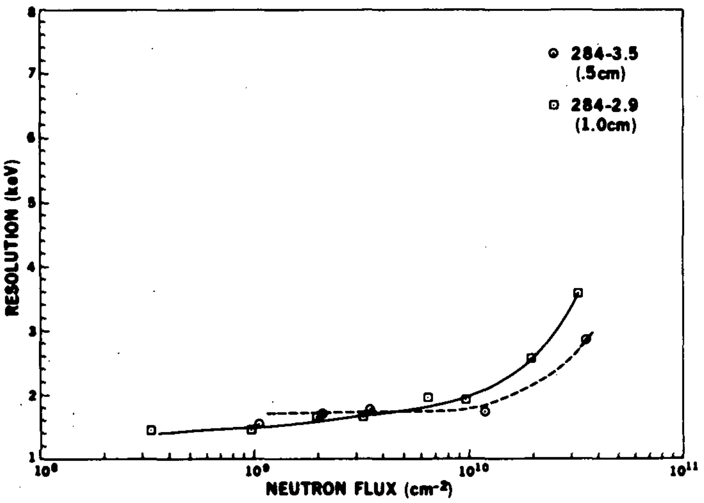

Fig. 5. RFWHM of two adjacent devices having different thicknesses, plotted as a function of neutron flux.

CONCLUSIONS

In order to correctly analyze and interpret the results of any neutron damage experiment involving high-purity germanium detectors a number of parameters and boundary conditions must be considered. One of the most fundamental of these is the electric field. Unless the carriers are at or near saturation velocity (i.e., fields $\geqslant$ 1000 Vcm^{-1}) results from different detectors will not be comparable. By comparing detectors made from germanium with different material parameters, we have established that none of the parameters tested give large differences (i.e., order of magnitude) in response to radiation damage.

At the most a 40% increase in the damage resistance was observed for two detectors--one grown in N_2 and one grown in H_2 and annealed. This result suggests that as hydrogen plays a role in modifying the electrical behavior of germanium as in other cases.[6,10,11] It should be emphasized that other material parameters remain to be examined. Work on the effects of doping germanium with some group II elements suggests that the germanium may be made more "radiation hard".[14,15]

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REFERENCES

1. F.S. Goulding and R.H. Pehl, IEEE Trans. Nucl. Sci., NS-19, No. 1, 91 (1971).

2. H.W. Kraner, R.H. Pehl and E.E. Haller, IEEE Trans. Nucl. Sci., NS-22, No. 1, 149 (1975).

3. L. Stewart, Phys. Rev., Vol. 98, No. 3, 740 (1955).

4. G. Ottaviani, C. Canali, F. Nava and J.W. Mayer, J. Appl. Phys., Vol. 44, No. 6, 2917 (1973).

5a) E. Sakai, H.L. Malm and I.L. Fowler, Semiconductor Nuclear Particle Detectors and Circuits, Nat. Acad. of Sci. Pub. 1593 (1963).

5b) M. Martini, J. W. Mayer, K. R. Zanio, Applied Solid State Science, Vol. 3 (1972).

6. W.L. Hansen and E.E. Haller, IEEE Trans. Nucl. Sci., NS-19, No. 1, 260 (1972).

7. R.N. Hall, IEEE Trans. Nucl. Sci., NS-19, No. 3, 266 (1972).

8. R.H. Pehl Lawrence Berkeley Laboratory, private communication.

9. L.S. Darken, Jr., T.W. Raudorf, R.C. Trammel, R.H. Pehl and J.H. Elliott, Nucl. Inst. and Meth. (to be published).

10. E.E. Haller, G.S. Hubbard and W.L. Hansen, IEEE Trans. Nucl. Sci., NS-24, 48 (1977).

11. G.S. Hubbard and E.E. Haller, Journal of Electronic Materials (to be published).

12. R.J. Fox, IEEE Trans. Nucl. Sci., NS-13, No. 3, 367 (1966).

13. A.J. Tavendale et al, Australian Atomic Energy Commission, private communication.

14. Y.A. Borodovskii, G.M. Gavrilov, L.A. Goncharov, P.D. Kervalishvili, P.G. Litovchenko and A.M. Khorvat. Sov. Phys. Semicond. Vol. 11, No. 10, Oct. 1977.

15. L.A. Goncharov, T.N. Dostkhodzhaev, V.V. Emtsev, T.V. Mashovets and S.M. Ryvkin. Sov. Phys. Semicond., Vol 11, No. 5, May 1977.

TABLE I

Detector	Thickness (cm)	Typeness	Net Impurity Concentration (cm^{-3})	Comments
284-2.9	1.0	P	9×10^9	"Standard" crystal growth: 1 atm H_2, quartz crucible.
284-3.5	0.5	P	1×10^{10}	"Standard" crystal growth.
436-2.8	0.5	P	7×10^{10}	Doped with 4×10^{17} cm^{-3} Si, 1 atm H_2, quartz crucible.
497-6.8A	0.5	P	2×10^{10}	"Standard" crystal growth; annealed 400 hr at 400°C in Bi-Pb.
564-12.3	0.5	P	4×10^9	Graphite crucible, $[O_2] \sim 5 \times 10^{12}$ cm^{-3} (possibly low Si conc.) 1 atm H_2
606-8.0	0.5	P	4×10^{10}	1 atm N_2, quartz crucible, $[O_2] \sim 10^{14}$.
612-9.6	0.5	N	4×10^{10}	1 atm deuterium, quartz crucible.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720