A HIGH RESOLUTION SEMICONDUCTOR DETECTOR FOR APPLICATIONS IN SPACE †

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Nuclear radiation detectors with volumes of ~1 cm^3 have been fabricated from single crystals of Germanium-Silicon alloy containing as much as 20 weight percent germanium. The properties of these detectors have been investigated and will be discussed. Tests reveal that the gamma ray photoelectric peak efficiency of an alloy detector with only 12 weight percent germanium is ~4 times that of a silicon detector of equal volume. The alloy detector will operate with excellent energy resolution at -75°C. Operation at room temperature appears to be a good possibility. Storage for long periods at room temperature does not seem to adversely affect these devices. The results of preliminary radiation damage experiments suggest that the alloy detectors possess a radiation damage resistance far greater than that of silicon.

INTRODUCTION

The superior energy resolution obtainable with semiconductor nuclear radiation detectors has made their use widespread in all fields involving gamma ray and charged-particle spectroscopy. For the purpose of nuclear spectroscopy in space, it is desirable to have a detecting device which will yield the best (lowest) energy resolution, the highest detection efficiency, and the fewest operating difficulties. In addition this detector should be light weight, rugged in construction, use little power, be able to operate at temperatures above -195°C, have room temperature storage capability, and the ability to withstand considerable damage from the high radiation zones in space. Unfortunately at present these attributes are not all combined in any one type of detector. Sodium Iodide is relatively efficient as a gamma ray detector. However, due to the relatively poor resolution of sodium iodide it becomes extremely difficult to extract accurate energy and intensity information from spectra containing more than a few lines. Conversely semiconductor detector spectra containing hundreds of lines can be accurately analyzed for energy and intensity information. The most commonly used semiconductor detector materials are germanium and silicon.

The photoelectric interaction probability for a gamma ray is roughly proportional to the fifth power of the atomic number (Z) of the stopping material. Thus, because of its low Z(14), silicon is very poor relative to germanium (Z=32), for detection of gamma rays. Silicon detectors do have an advantage over germanium detectors in that they can be operated and stored at room temperature. This room temperature operating ability stems from the larger band gap possessed by silicon (1.2 eV). The narrower band gap of germanium (0.7 eV) requires that the detector be cooled to the point at which thermal generation of carriers across the gap does not interfere with detection of the ionizing radiation. The lithium, used to compensate the impurities present in the detector, does not precipitate in silicon at room temperature as it does

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in germanium. Such precipitation renders the detector useless.

The ideal detector for space applications would combine the high resolution, good gamma ray efficiency and large detector volume available in a germanium detector with the desirable properties of a silicon detector. These properties include room temperature operating capability, and prolonged room temperature storage capability. Such an ideal detector can, in principle, be obtained by judiciously alloying germanium and silicon in a large single crystal. Figure 1, taken from the work of Braunstein et al[1], gives the dependence of the germanium-silicon alloy band gap on the percentage of the constituents present. From this figure it becomes apparent that a silicon content of at least 15 atomic percent should be present in the alloy. At this silicon concentration the crystal has a band gap almost midway between that of germanium and silicon but has retained a large germanium concentration which will yield a high gamma ray efficiency. It may be necessary to push the silicon concentration still higher in order to produce a wider band gap and thereby permit the detector fabricated from this material to operate at more elevated temperatures.

In pure silicon as in pure germanium both interstitials and vacancies are sufficently mobile to interact with dopants and other defects so as to produce stable secondary complexes. Removal of these radiation induced complexes by annealing requires a temperature so high as to destroy the properties of the germanium and silicon which enable it to function as a detector. In the germanium-silicon alloy, the formation of complexes will be hindered not only by the low vacancy-interstitial mobility but also by the thermal annealing which may be expected to proceed at reduced temperature. If the detector bias is maintained during the annealing cycle, the resulting lithium ion drift will tend to compensate both primary and secondary damage effects. Such an "in situ" cycling procedure should enable greatly extended detector operating lifetimes.

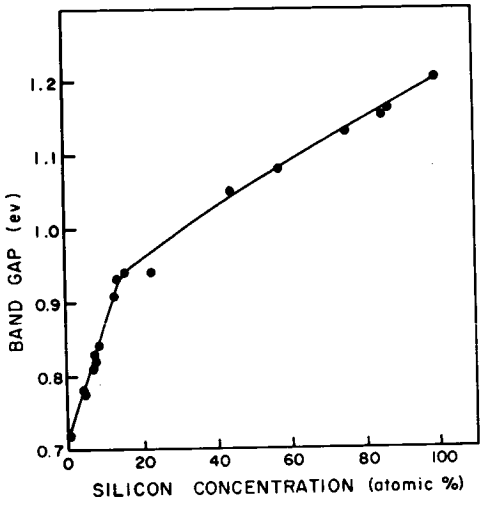

Figure 1. Variation of germanium silicon alloy band gap with silicon concentration[1].

GERMANIUM-SILICON ALLOY SINGLE CRYSTALS

It has been found that extremely high purity levels are requisite in silicon and germanium for fabrication of good detectors. The presence of such contaminants as copper, carbon or dissolved gases, particularly oxygen, in quantities as small as 1 contaminant atom in 10^9 silicon or germanium atoms is sufficient to degrade detector performance. This effect is rendered through trapping of the charge carriers and/or breakdown of the large electric field which must be applied across the detector in order to collect these carriers. The specifications

for germanium-silicon alloy crystals used for nuclear radiation detector fabrication are consistent with the crystal requirements necessary to produce good germanium or silicon detectors.

In this experiment measurements were made of those crystal parameters which most strongly influence radiation detector performance. These parameters include: minority carrier lifetime, trace oxygen content, homogeneity and degree of crystaline perfection, lithium drift mobility, and lithium diffusion constant. The measurements which define the last two quantities are detailed below.

The rate at which lithium can be drifted into germanium-silicon alloy under the influence of an applied electric field was studied, in a sample containing 10% Ge - 90% Si, as a function of temperature in the range 100°C to 160°C. The lithium drift rate is an important quantity in that it reveals how deeply a germanium-silicon alloy slice may be lithium compensated in a given time period. The drift depth measurements were performed by vacuum evaporating lithium onto the face of a germanium-silicon alloy slice, then heating at 400°C for 10 minutes in an argon atmosphere furnace, and then drifting in a silicone fluid medium maintained at the desired temperature. The progress of the n-i and i-p juntions were monitored by the copper stain technique. The change in depth of the intrinsic region was followed at a given temperature for about 12 days with a fixed applied reverse bias of 75v. Intrinsic depth versus drift time curves as measured for this alloy sample are plotted in Figure 2 for temperatures of 120°C, 140°C and 150°C. Comparison drift curves for germanium and silicon are also presented. It may be observed that the germanium-silicon alloy drifts considerably more slowly than either germanium or silicon.

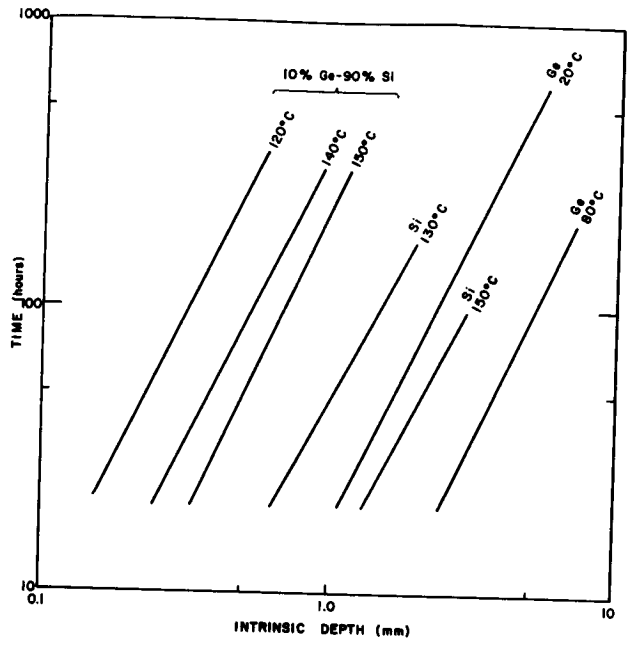

Figure 2. Lithium drift depth in germanium-silicon alloy, containing 10% Ge - 90% Si, as a function of time at various temperatures. The bias applied across the detector was 75 volts. Also plotted are comparable curves for germanium and silicon.

In order to make good semiconductor diodes it is necessary to diffuse lithium into the material to just the proper depth. If lithium is diffused too deeply, a thick "dead layer" results on the face of the detector. If lithium is not diffused deeply enough, oxidation and surface preparation will remove the lithium before it can be drifted into the material. Although the germanium-silicon alloy under study is silicon-rich, it is not at all obvious that the diffusion rate of the alloy will be expressible as some linear combination of the diffusion constants for germanium and silicon. Therefore, the diffusion of lithium in the germanium-silicon alloy is being studied as a function of temperature and Ge/Si ratio. In this study lithiated slices of both silicon and germanium-silicon alloy were heated to a preselected temperature. The slices were removed from the oven and the diffusion depth was determined by the copper stain technique.

From this data plus a knowledge of the surface lithium concentration and the acceptor dopant level, the lithium diffusion coefficient could be calculated for a particular diffusion temperature and Ge/Si ratio.

The results of the measurements described above are shown in Figure 3 where D is plotted versus the reciprocal of the absolute temperatures for pure silicon specimens, for samples from an ingot containing 10% germanium by weight, and for samples from an ingot with 16% germanium by weight. The solid line shown is based on Pell's empirical equation[2] for the diffusion constant of lithium in silicon. The data from the measurements on the alloy samples and the silicon samples agree with Pell's estimates above 500°K. Below this temperature there is departure of the data for the alloy samples from both Pell's curve and from the data for silicon. This deviation is consistent with an oxygen concentration of 10^{17} atoms/cm^3 in the base alloy. The effects of this oxygen on the diffusion constant become more pronounced as the diffusion temperature is lowered.

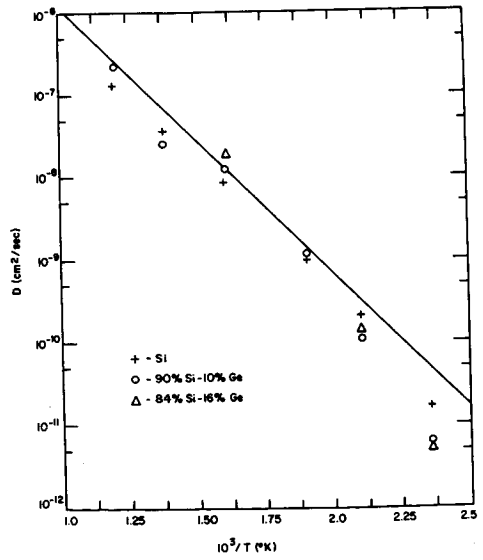

Figure 3. Diffusion constant for lithium in germanium-silicon alloy and in silicon at various temperatures. Also shown as a solid line is Pell's relation for silicon[2].

BEHAVIOR OF Ge-Si ALLOY DETECTORS

A number of gamma ray and charged particle detectors have been fabricated from germanium-silicon alloy. Due to the very low drift rate of lithium in the germanium-silicon alloy ingots, most detectors had active depths ranging from 200 to 800 μ. This depth corresponds to about 1 month of drift time and yields maximum active volumes of ~1 cm^3.

The alloy detectors deliver good gamma ray resolution at temperatures up to -75°C. At room temperature the resolution is greatly degraded due to surface leakage. A grooved or guard ring detector configuration would substantially improve this response. Typical alloy detector gamma ray resolution values range from 2 to 5 keV for ^{57}Co gamma rays. Comparable resolution is obtained using germanium detectors of the same size. At 356 keV the photopeak gamma ray efficiency of an alloy detector containing 12% Ge - 88% Si is 4 times that of a silicon detector of the same size.

Several alloy detectors have been stored for periods of up to 3 months at room temperature while exposed to the room atmosphere. In all cases it was possible to operate these devices, when they were coooled back down to -175°C, with no loss in resolution or degradation of reverse bias characteristics.

As described in reference 3, germanium-silicon alloy detectors have also been used for detection of alpha particles yielding extremely good spectral energy resolution. Application of a thin gold entrance window on the p-face of the diode yields an ^{241}Am spectrum such as that presented in Figure 4.

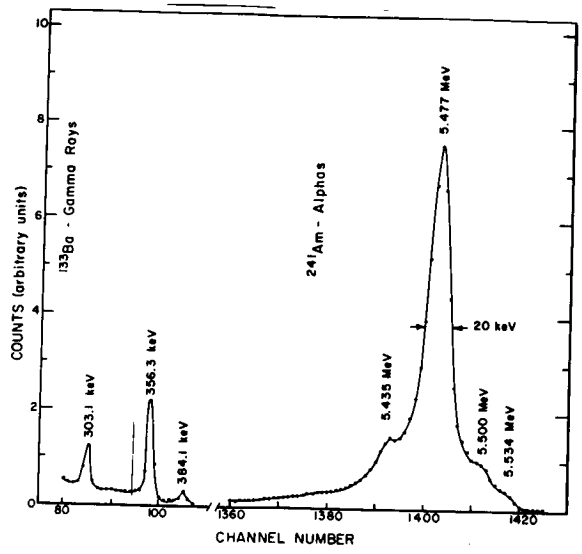

Figure 4. ^{241}Am alpha spectrum as observed with a germanium-silicon alloy detector. The ^{133}Ba gamma ray spectrum observed at the same time is used for energy calibration purposes.

RADIATION DAMAGE MEASUREMENTS

The germanium-silicon alloy detectors described in the preceding section have been employed to study the effects of gamma ray damage on detector performance. Exposure to the gamma rays was accomplished in the 3000 Curie ^{60}Co hot cell facility of the Rutgers University Reactor. Four lithium-drifted diodes were exposed to gamma radiation. Two of the diodes had been fabricated from 1000 ohm-cm boron-doped silicon, while the remaining two diodes were made from 300 ohm-cm gallium-and-boron-doped germanium-silicon alloy (88% Si, 12% Ge by weight). The four diodes were mounted on a copper plate in the vacuum space of a liquid nitrogen cooled cryostat. The diodes were maintained under vacuum and at liquid nitrogen temperature throughout the irradiation and during the post-radiation measuring period. The gamma flux to which the diodes were exposed was 1.3×10^{15} photons/cm^2 per hour, which is equivalent to a dose rate of 217 rads (Si)/sec. They were exposed for an accumulated period of 1,006 minutes, to a total fluence of 2.14×10^{16} photons/cm^2.

During the course of the above experiment measurements were periodically made of the detector: reverse-bias leakage current, reverse-bias photocurrent induced by the ^{60}Co gamma ray fluence, and resolution. The resolution of the silicon detectors was observed to degrade many times faster than the alloy detector resolution. The ^{57}Co gamma ray spectra observed with one of the germanium-silicon detectors both before and after exposure to 2×10^{16} photons/cm^2 is presented in Figure 5. A similar set of spectra for one of the silicon detectors is presented in Figure 6. The resolution of both of the silicon detectors was greatly degraded by the radiation damage while the alloy detectors were hardly affected. Post-irradiation annealing at several temperatures up to 273°K, completely restored the properties of the two alloy detectors while similar annealing caused a monotonic deterioration in the resolution of the silicon detectors. The resolution of the silicon detectors did not fully recover even after 24-hour lithium-ion drift cycle at

360°K. The reverse bias current measurements are also consistent with the above data. Additional details of these experiments will be presented in another publication.

CONCLUSION

A number of points concerning the properties of germanium-silicon alloy remain to be clarified by future experiments. Some conclusions concerning this material, based on the experiments described in this paper, are listed below.

1. Germanium-silicon alloy single crystals of detector grade can be produced with as much as 20 weight percent germanium.
2. Lithium can be drifted into these crystals to compensate them to reasonable depths.
3. Detectors of volumes ~1 cm^3 have been achieved and these yielded gamma ray resolution comparable to that of a silicon detector of similar size.
4. Alloy detectors have been found to possess a gamma ray efficiency significantly better than that of silicon detectors of comparable volume.
5. The alloy detectors work quite well at -75°C and with geometric alterations will probably function at room temperature.
6. Long term room temperature storage does not appear to harm the alloy detector.
7. The alloy detector appears to evidence a gamma ray radiation damage resistance greatly exceeding that of silicon (and implicitly germanium).
8. Annealing the alloy detector at temperatures below 300°K appears to remove the effects of the radiation damage. In silicon similar thermal treatment of gamma irradiated detectors is found to cause additional degradation.

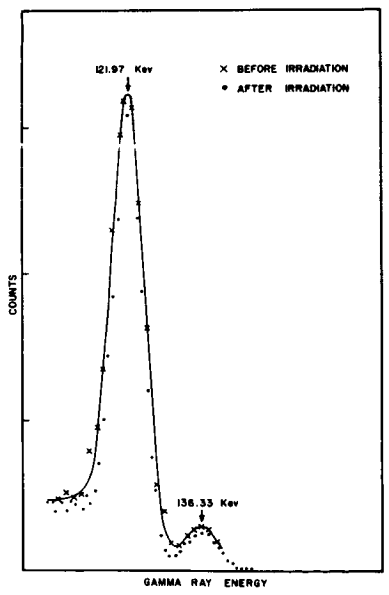

Figure 5. ^{57}Co gamma ray spectra taken with an alloy diode before and after irradiation.

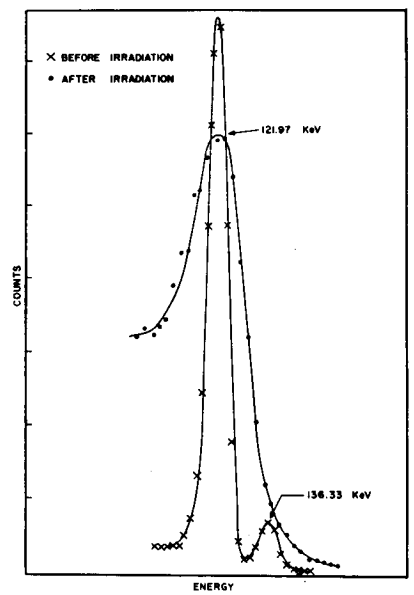

Figure 6. ^{57}Co gamma ray spectra taken with a silicon detector before and after irradiation.

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