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InSb AS A γ-RAY DETECTOR

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Abstract:

The III-V semiconductor InSb has the potential for being a superior γ-ray detector, with a possible improvement over Ge by the factors: resolution, 2×; peak-to-Compton ratio, 12×; efficiency (per mole), 9×. Recent availability of "intrinsic" InSb, coupled with pulse-height discrimination techniques to overcome geometrical dependence on charge collection, make it feasible to investigate the practicality of this material for producing detectors. We discuss its advantages and disadvantages.

1. Introduction

Since the introduction in the early 1960's of Ge(Li) detectors for γ-ray spectroscopy, almost constant efforts have been expended to enlarge them, make them more uniform, and improve their stability; this in addition to increasing their resolution and peak-to-Compton ratios. Great strides have been made in going from the original small Ge(Li) detectors to the present "large-volume" intrinsic p- or n-type Ge detectors. In addition, much of the recent work has centered on elaborate Compton-suppression spectrometers, using NaI(Tl) or BGO ("bismuth germanate") shields [1,2], and on electronic pulse-shape discrimination techniques [3,4] to correct for damage and non-uniformities in charge collection. Although present technology has quite a way to go to attain the theoretical limits on resolution and peak-to-Compton ratios, we are witnessing signs of diminishing returns with respect to effort and expenditure versus improvement. Thus, it is worth while investigating possible alternative materials to Ge for fabricating high-quality γ-ray detectors.

A significant amount of research has gone into investigating other semiconductors, most notably the III-V and II-VI mixed semiconductors [5]. Most of the effort, however, has gone into investigating large band-gap materials that would serve as useful compromises between Ge and NaI(Tl): having resolution far better than NaI(Tl), if not comparable with that of Ge, but not requiring the cumbersome cryogenics of Ge. As a result, CdTe, and to a lesser extent, GaAs and HgI_2, detectors are now commercially available.

Our interests lie in the opposite direction -- investigation of small band-gap semiconductors (with a large Z, if possible) that could provide even better resolution and peak-to-Compton ratios than Ge, but, on the other hand, most likely would be even more tricky and cumbersome to use. Of the possible semiconductors, the III-V compound InSb stands out in all respects. It could potentially replace Ge as the "γ-ray detector of the next generation," but it will require considerable technological development before its potential can be realized. Its properties are compared with those of other detector semiconductors in table 1.

2. Properties of InSb

InSb is a material of extremes: Its potential advantages over Ge are formidable, although so are its drawbacks. Because its positive attributes are relatively straightforward, they require little explanation. Its pitfalls are not so obvious and thus require more detail, but this should not be taken to mean that they outweigh its advantages. Any very-high-resolution detector can be expected to be tricky to deal with, and InSb should prove to be no exception. In addition, many of the semiconducting properties of InSb are not so well known as they should be, and there is considerable variation in the literature. In the following, we have always chosen the pessimistic numbers, so InSb should be at least as good as represented here, and most likely considerably better.

From table 1 it can be seen that, in principal, InSb should make a superior γ-ray detector. Since the photoelectric effect scales as Z^5, the InSb effective Z of 50 results in an efficiency (per mole) of 9.3 times that of Ge and a linear stopping power somewhat higher if the differences in densities are folded in. Also, single-event Compton scattering scales as Z, so if the resolutions of InSb and Ge were comparable, InSb would have a peak-to-Compton ratio 6 times better than Ge -- this on the basis of Z alone. (And, of course, assuming comparably sized detectors, which is not a reality at this time.)

The resolutions are not comparable, however, for the InSb band gap is much smaller, 0.165 vs 0.67 eV (at 290 K). The contribution to resolution (in eV) due to the statistics of charge collection is given by

$$\Delta E_F = 2.355\ (F\varepsilon E_\gamma)^{1/2}, \qquad (1)$$

where F is the Fano factor, ε is the average energy (in eV) needed to form an electron-hole pair, and E_γ is the γ-ray energy (in eV). Assuming ε to scale with the band gap and the Fano factor to be comparable to that for Ge, this yields a resolution for InSb better than that of Ge by a factor of at least two. Folding this in, we obtain a peak-to-Compton ratio improved by a factor of at least 12.

Unfortunately, difficulties immediately arise, for the total spread in resolution comes from several sources. It can be summarized by

$$\Delta E = (\Delta E_n^2 + \Delta E_{col}^2 + \Delta E_F^2)^{1/2}, \qquad (2)$$

these three terms being the contribution from electronic noise in the preamplifier-detector system, the contribution resulting from incomplete charge collection, and the statistical contribution just discussed. A glance at the relative electron/hole mobilities shows the source of the difficulties: the electron mobility is faster than the hole mobility by a factor of 100. (Actually, this is just one aspect of the properties of InSb that is not completely understood; values of the electron/hole mobility ratio given in the literature vary from 100 down to about 20.) This leads to three separate, but related, problems.

First, the problem of compensation. In the early days of Ge detector fabrication, when "intinsically pure" Ge was not available, it was possible to compensate p-type Ge by drifting it with Li^+ ions. The electron/hole mobilities in Ge differ only by a factor of two, so p-type Ge is easy to produce, and drifting can be carried out in a reasonable amount of time at elevated temperatues (approaching 100°C). Thus, for many years Ge(Li) detectors were the main standby. Drifting InSb, however, is out of the question: The difference between the electron and hole mobilities means that Li^+ drifting of p-type InSb is impossible; indeed, p-type InSb itself is not readily produced. Instead, drifting n-type InSb with a small anion would be necessary, and F^-, the smallest anion, is many times as large as Li^+. And the small InSb band gap makes drifting at elevated temperatures unfeasible, so drifting becomes impossibly slow.

The solution to this first problem is to be able to fabricate detectors from "intrinsic quality" InSb. Zone-refining techniques have now developed to the point that such quality InSb is becoming commercially available, at least for very small infra-red detectors.

Second, the problem of complete charge collection. The efficiency of charge collection at a distance x from the negative contact in a detector is given [6] by

$$\eta = \frac{Q}{Q_o} = \frac{\lambda_e}{L}(1-\exp[-\frac{L-x}{\lambda_e}]) + \frac{\lambda_e}{L}(1-\exp[\frac{-x}{\lambda_h}]), \qquad (3)$$

where η is the ratio of the collected charge (Q) to the total deposited charge (Q_o), λ_e and λ_h are the respective electron and hole trapping lengths (in cm), and L is the detector thickness (in cm). The electron and hole trapping lengths are given by

$$\lambda_e = \mu_e \tau_e E \qquad (4)$$

and

$$\lambda_h = \mu_h \tau_h E, \qquad (5)$$

where the μ's are the respective electron and hole mobilities (in $cm^2/V \cdot sec$), the τ's are the respective trapping times (in sec), and E is the applied electric field (in V/cm). From these equations it can be seen that the relatively slow hole mobility is a potential source of trouble. Energy resolutions of a few percent require an η of at least 90%, and resolutions approaching those of the best Ge detectors will require a much higher value, approaching 98 percent or better. Thus, the parameter λ_h/L will necessarily have to be at least 10 or better, and this may prove to be a severe limitation on the size of high-quality detectors.

The solution to this second problem is not quite so straightforward as the solution to the first one, and it may turn out to be very difficult to produce decent "large" InSb detectors. It should be noted that there are stoichiometric problems associated with growing extremely pure crystals of mixed semiconductors that are not encountered in growing extremely pure crystals of Si or Ge. However, it should be noted that the hole mobility in InSb, even though much slower than the electron mobility, is still considerably faster than the hole mobility in CdTe or HgI_2, so incomplete charge collection per se will probably not be quite so severe a problem with InSb as it is for those materials [5].

Third, the problem of geometry on charge collection and resolution. Trapping and incomplete charge collection would not be such a problem if it were possible to guarantee uniformly incomplete charge collection. Unfortunately, this approaches becoming possible only for very small detectors. As a result, detectors fabricated out of materials having widely different electron and hole mobilities show a decided geometrical dependence on the degree of (hole) trapping and thus a dependence on where in the detector the γ-ray interaction took place. Interactions taking place near the negative contact, in which the electrons traverse the entire width of the detector, show much more complete charge collection than do interactions taking place near the positive contact.

Luckily, the very cause of the difficulty, i.e., the differences in mobility, also furnishes a solution to this third problem. There is a similar geometrical dependence on pulse rise-time, with pulses having more complete charge collection being faster than those having less complete charge collection. Two types of electronic pulse-height correction have been developed to compensate for this. The first was developed to compensate for this problem in HgI_2 detectors [4]. The second was developed in our laboratory to compensate for varying incomplete charge collection in neutron-damaged Ge detectors [3]; it can also compensate for geometrical effects on rise-time in coaxial detectors. Both methods are equally applicable to solving this problem with InSb, requiring only slightly more complex electronics than are normally used for self-gated-singles coincidence experiments.

3. Summary and Prospects for InSb as a Practical γ-Ray Detector

On paper InSb shows great potential for fabricating superior γ-ray detectors. However, it is decidedly not an easy material to deal with, and we have covered some of its pitfalls. What about practical γ-ray detectors?

InSb cannot be drifted for compensation, but it shows promise for becoming available in quality good enough for "intrinsic" detectors, requiring no compensation. It has no destructive solid-state phase transitions (as contrasted with materials such as HgI_2), and zone-refining techniques have reached the point that very small "intrinsic" detectors are now commercially available for infra-red spectroscopy. The promise of InSb is great enough that working out techniques for dealing with it should definitely be worth the effort. We are currently in the process of converting and testing several of these detectors for γ-ray spectroscopy. Results should be forthcoming in the near future.

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Table 1

Comparison of Semiconductor Properties at 290 K

	Si	Ge	InSb	GaAs	CdTe	HgI_2
Z	14	32	49:51	31:33	48:52	80:53:53
Band Gap (eV)	1.107	0.67	0.165	1.35	1.44	2.13
Density (gm/cm^3)	2.33	5.32	5.78	5.32	5.86	6.36
Lattice Constant (Å)	5.43	5.65	6.48	5.65	6.48	[a]
Electron Mobility (cm^2/V•sec)	1 900	3 800	78 000	8 800	1 200	≈100
Hole Mobility (cm^2/V•sec)	500	1 820	750	400	50	≈10

[a] All have cubic lattices (diamond or zincblende), except for HgI_2, which has a tetragonal lattice, with a = 4.37 and c = 12.44 Å.