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ION IMPLANTED HIGH-PURITY GERMANIUM DETECTORS

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Low energy boron and phosphorus ions have been used to implant a p^+-i-n^+ structure in germanium with net concentrations of the order of 10^{10}–10^{11} donors/cm^3. At 77 K, resolutions of better than 20 keV and 30 keV (fwhm) have been obtained with ^{241}Am-α particles incident on the front-(p^+) and back-(n^+) contact, respectively, of the 2 mm thick device.

1. Introduction

Until now, ion implantation in germanium has been used only to produce thin window contacts on Ge(Li) detectors[1,2]. The advent of high purity germanium with net donor concentrations in the range 10^{10}–10^{11} cm^{-3} makes lithium compensation no longer necessary for devices with depletion layers up to 5 mm. Successful results of contact realization on such material by conventional methods have been reported by several authors[3–7]. Occasionally, contamination by a fast copper diffusion during the thermal treatments has been observed in these devices. The possibility to use ion implantation without high temperature cycles and the advantages of boron as dopant have been shown by the Strasbourg group[8]. We have extended these investigations, and in particular, we have tried to produce both the rectifying and the ohmic contact on N-type high purity material by implanting low energy boron and phosphorous ions, respectively, and choosing the experimental conditions in such a manner to keep annealing treatments below 300° C.

2. Choice of the implant conditions

As previously published[9]) we have determined doping profiles and sheet resistivity of B^+ and P^+ implants in germanium, as a function of several parameters, by the Van der Pauw technique. The data of interest here have been summarized in fig. 1 for boron and phosphorus respectively. It appears that for boron implantations, the carrier concentration remains essentially constant for annealing steps below 400° C. As a consequence, no thermal treatment is necessary at all. In order to reduce the penetration of the ions and to keep the window thickness as small as possible, the lowest implant energy is recommended. In the case of phosphorus, an annealing treatment is necessary. To avoid copper diffusion this temperature should be

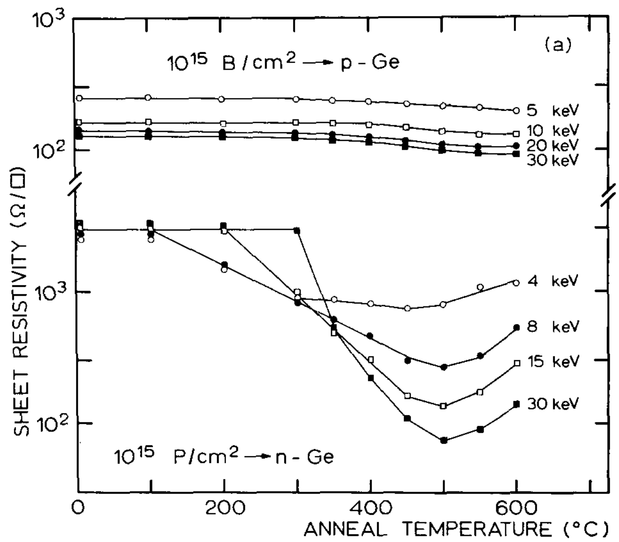

Fig. 1a. Sheet resistivity vs anneal temperature for boron and phosphorous implants of several energies.

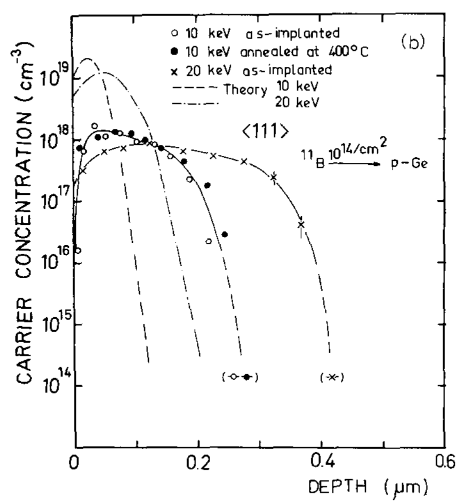

Fig. 1b. Carrier concentration profile of 10 keV and 20 keV boron implanted into ⟨111⟩ Ge.

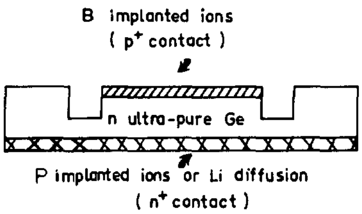

Fig. 2. Detector configuration.

as low as possible, which is the case for low energy implantations. The following experimental conditions have been found satisfactory for N-type samples:

P^+ layer: 10–20 keV boron ions with a dose of 10^{14} cm^{-2},

N^+ layer: 4 keV phosphorus ions with a dose of 10^{14} cm^{-2} and annealing at 300° C, called below Ge(B,P), *or* Li-diffusion at 350° C before the boron implantation, called below Ge(B,Li). In the latter case no annealing of the boron layer was done.

Under these conditions, our previously published doping profiles[9]) indicate that for both the P^+ and N^+ implanted layers, counters with dead zones of a few tenths of a micrometer should be achieved.

3. Detector preparation

Germanium samples with thicknesses ranging between 2 and 4 mm, with net donor concentrations between 2×10^{10} and 2×10^{11} cm^{-3}, cut in the ⟨100⟩ direction, have been implanted as described above.

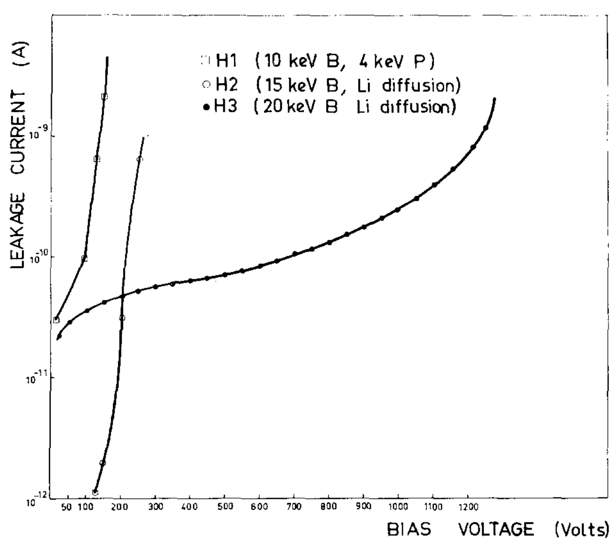

Fig. 3. Reverse characteristics of Ge(B,P) and Ge(B,Li) diodes. The different breakdown voltages indicate the strong influence of surface conditions.

The wafers were prepared by classical techniques. In order to reduce the leakage current of the counters an "inverted T structure" as proposed by Llacer[10]) is prepared (fig. 2) by an ultrasonic apparatus. Both thickness and depth of the groove are 1 mm.

Just before implantation the samples are etched in a 1 HF:3HNO_3 solution and rinsed in deionized water.

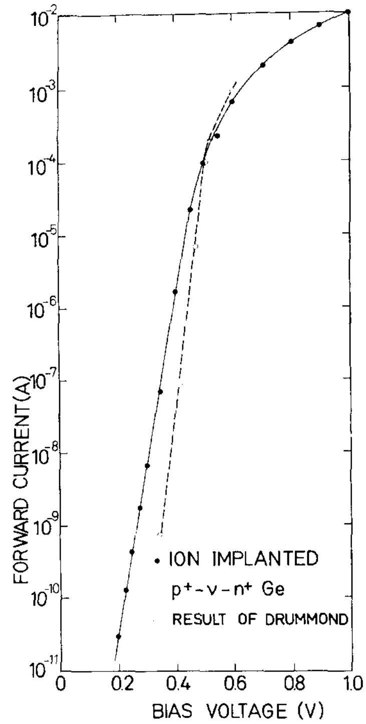

Fig. 4. Forward characteristic of a Ge(B,P) diode (full dots) compared to a diffused structure[7]) (open dots).

The samples having a phosphorus N^+ layer are annealed at 300° C for 30 min in vacuum ($p \simeq 10^{-6}$ torr) in a clean system made of high purity quartz ("suprasil"). The Li^+ coated samples are not annealed after the boron bombardment. Since the implantations are performed over the samples, the ions implanted outside the T structure are removed by etching, after masking the inner area with blackwax. Finally, the samples are cleaned and mounted in a cryostat and cooled to 77 K.

4. Detector properties

4.1. Electrical characteristics

Typical reverse characteristics are shown in fig. 3 for Ge(B,P) and Ge(B,Li) diodes. The leakage current at 77 K is generally less than 10^{-10}A for a bias voltage up to 100–200 V. The breakdown voltage depends on the surface conditions after chemical treatments. In some cases it exceeds 1000 V with a current less than 10^{10}A.

The forward characteristic of the Ge(B,P) diodes, displayed in fig. 4 indicates that a good contact is obtained, since a straight line extending over 7 decades could be measured. From the change of the slope in the high current region a series resistance less than 30 Ω (at 77 K) is derived. This result is in close agreement with the values of Drummond[7]) obtained by diffused and evaporated contacts. Capacitance measurements have been performed on several detectors as a function of the reverse voltage. It appears that the change of capacitance versus voltage above 1 V is small ($C \approx V^{-0.3}$). Surface barrier diodes prepared on the same material give nearly the expected square root dependence, as found also recently by Hansen[11]). Diodes prepared by boron implantation in less pure material ($\approx 10^{14}$ cm^{-3}) also show the square root dependence.

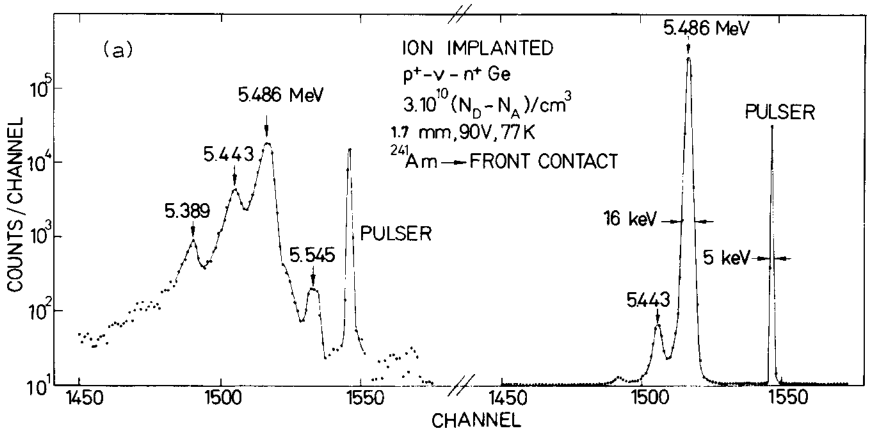

Fig. 5a. ^{241}Am α-spectrum in logarithmic and linear scales.

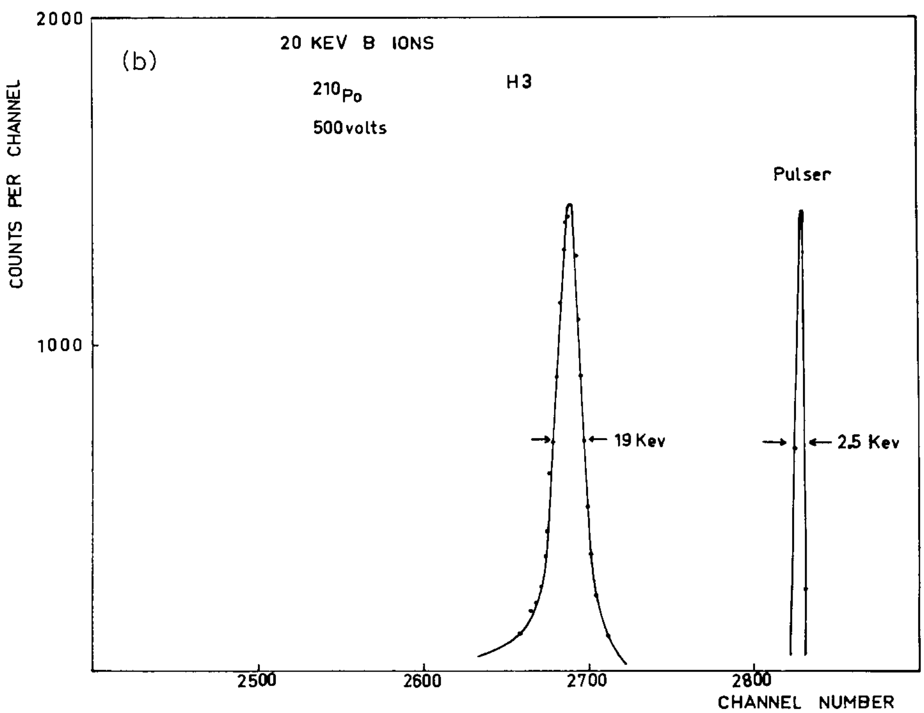

Fig. 5b. ^{210}Po α-spectrum.

At present time the origin of this behaviour is not well understood and further experiments are necessary. Either the high purity material is very sensitive to surface channels, or compensating centers are introduced.

4.2. Detector characteristics

Special emphasis has been given to an estimate of the window thickness. From the response of the detector to 5.5 MeV α-particles, it is possible to determine the dead layer, i.e. the location of the depletion zone with respect to the surface.

4.2.1. *Particles impinging through the B^+ layer*

For the detectors implanted with 10 keV B^+ ions, a resolution (fwhm) of 16 keV at 90 V was recorded for 5.5 MeV α-particles (fig. 5a). If we assume that the line broadening results essentially from statistical fluctuations in energy loss (straggling) in the window, we can estimate its thickness to about 2000 Å. This

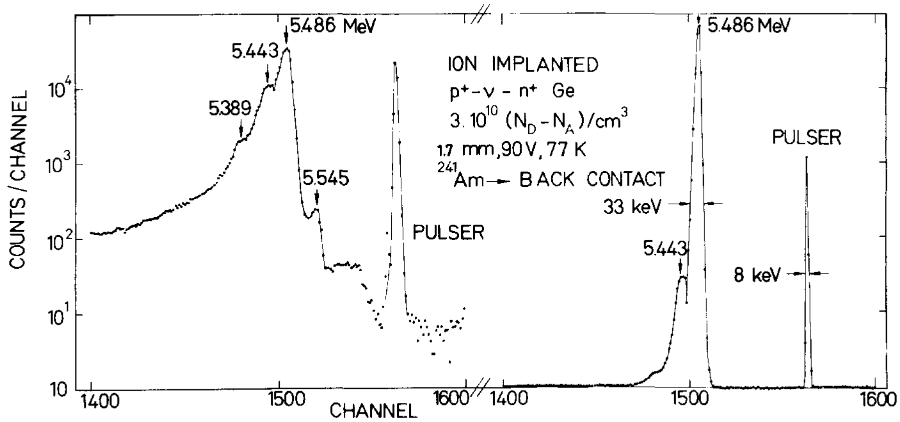

Fig. 6. ^{241}Am α-spectrum in logarithmic and linear scales. The particles enter through the back contact of a Ge(B,P) detector.

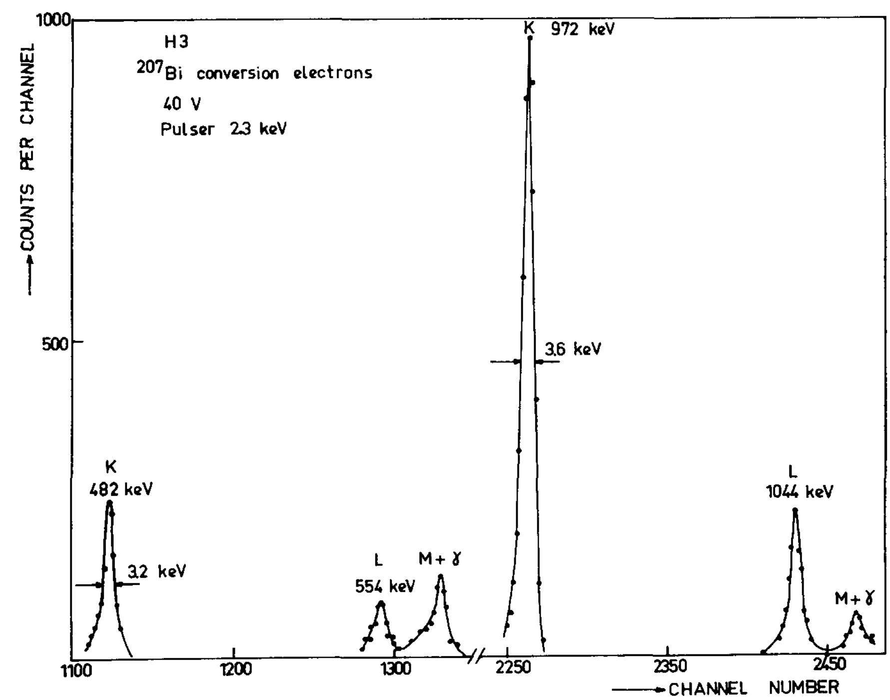

Fig. 7. ^{207}Bi conversion electron spectrum.

value is in good agreement with our previously published[9]) carrier concentration profiles.

For the 20 keV B^+ implanted layers (fig. 5b), the resolution (fwhm) was 19 keV at 500 V. This corresponds to a straggling through a 2500 Å thick layer of germanium.

4.2.2. *Particles impinging through the P^+ layer*

A 1.7 mm thick counter biased to 90 V has given a resolution of 33 keV for the 5.5 MeV α-particles. Again, if we suppose that energy straggling is the dominant parameter, this corresponds to an upper limit in window thickness of 8000 Å (fig. 6). Reduction of the applied voltage to 60 and 30 V resulted in a peak shift to lower energies of 20 and 50 keV, respectively. That is equivalent to an increase of the undepleted back zone of 600 and 1700 Å respectively. Full depletion of the 1.7 mm thick device is reached at about 25–30 V.

A typical conversion electron spectrum (^{207}Bi) is shown in fig. 7. The resolution of the 975 keV K-line is 3.5 keV. Tested with different γ-ray sources, these counters exhibited resolutions of 630 eV at 122 keV (^{57}Co) (electronic noise was 470 eV). The 1.17 MeV line of ^{60}Co was resolved with a fwhm of 1.7 keV (electronic noise was 600 eV) (fig. 9). The full energy peak is symmetrical, as shown by a gaussian scale plot, indicating a good carrier collection. This result is confirmed by the fact that both the pulse height and resolution are constant when the bias voltage is changed. No degradation in signal amplitude (less than 2 channel for a 3000 channels pulse height) and resolution (less than 50 eV in the case of ^{57}Co) is observed even at zero external voltage. The square of the intrinsic linewidth (experimental linewidth reduced by the contribution of electronic noise) of a small detector as a function of γ-ray energy is reported in fig. 10. The calculated line width due to pair creation statistics assuming a Fano factor of 0.07 is plotted on the same figure. The small difference between the experimental ($F \approx 0.115$) and calculated curves is a further indication of good charge collection efficiency.

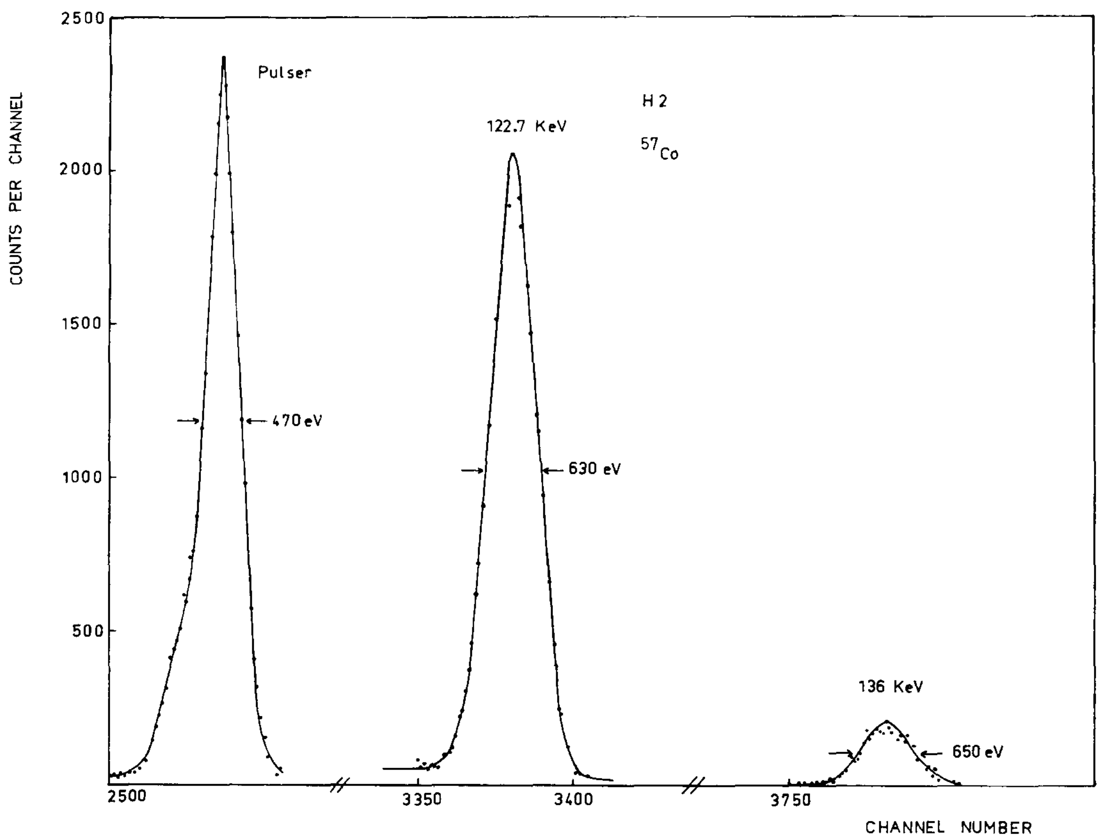

Fig. 8. γ-spectrum of ^{57}Co.

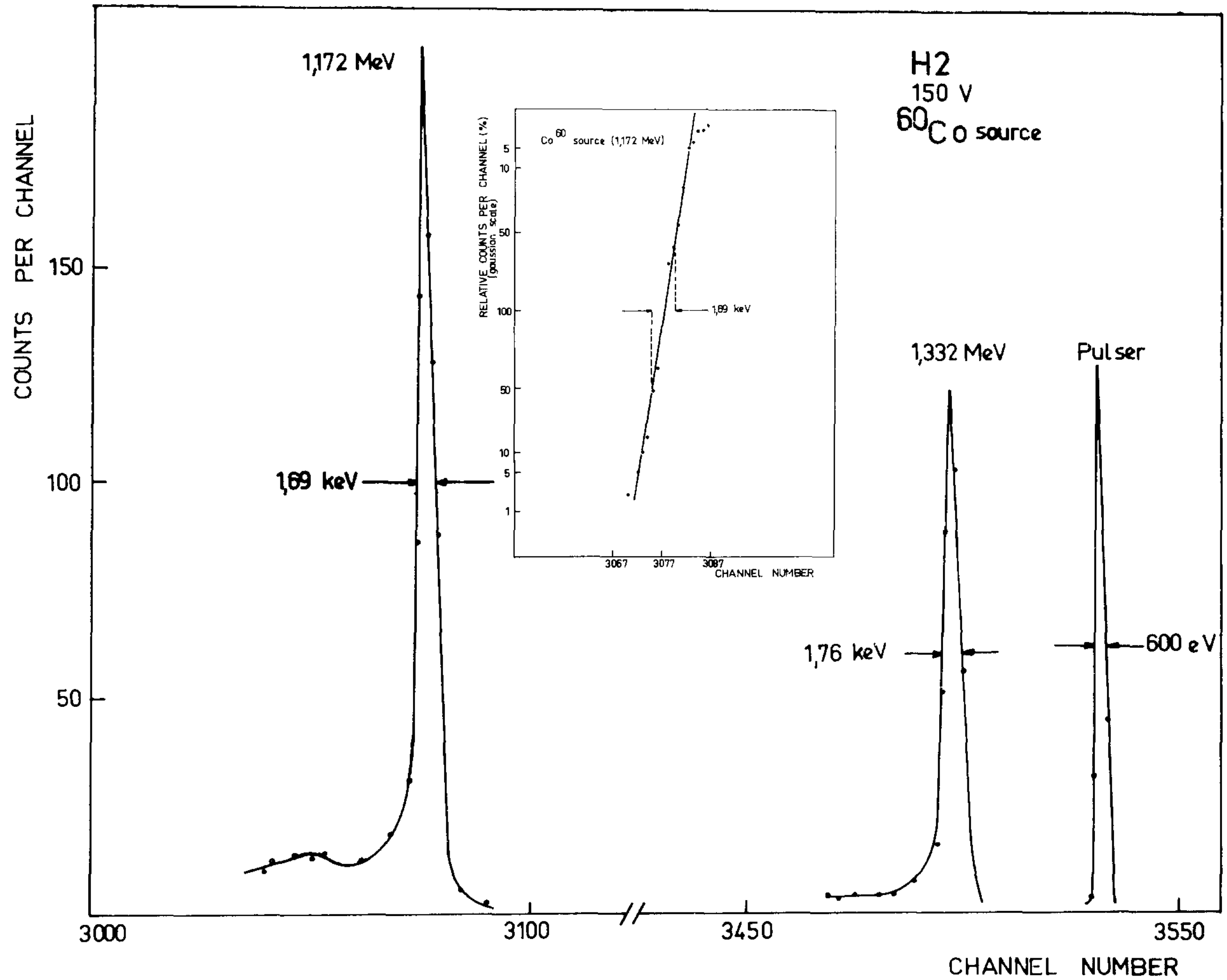

Fig. 9. γ-spectrum of ^{60}Co. The insert displays the 1.17 MeV peak in a gaussian plot.

5. Discussion

Both the capacitance and spectroscopic measurements have shown that a 1.7 mm thick Ge(B,P) diode is fully depleted at about 25 V. The net donor concentration calculated from these data gives a value of $\approx 10^{10}$ cm^{-3}, which is a factor ≈ 3 smaller than the manufactured value. We think that this discrepancy is not significant, since the evaluation of the electrical properties of this material is extremely difficult. Thus, we conclude that if any compensation centers have been introduced by our procedure, their number seems to be small as compared to those usually encountered after forming contacts by heat treatments[6]).

We have shown that the window thicknesses calculated on the diverse contacts are in fairly good agreement with those one would expect from the location of the junction obtained by doping profile measurements. It is possible that even thinner windows, and perhaps better resolutions for charged particles can be obtained by implanting still at lower energies.

Thus, germanium of high purity is a very attractive material for preparation of nuclear radiation detectors, not only with respect to photon spectroscopy, but also to detection of charged particles. In agreement with other authors, the main advantage over the classical Ge(Li) counters are:

- absence of lithium compensation, which enables the fast production of large sensitive layers in sufficient pure material,
- absence of lithium precipitation,
- possibility of storage at room temperature without degradation,
- absence of trapping effects.

The ion implantation technique applied to this ma-

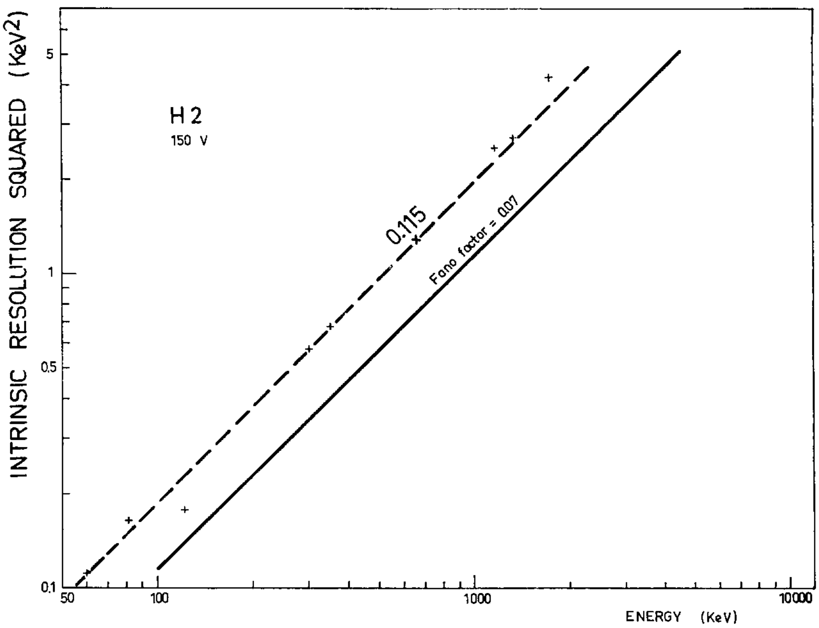

Fig. 10. Intrinsic resolution of a detector, i.e. the measured line-width reduced by the contribution of the electronic noise, as a function of photon energy.

terial yields in detectors characterized by low leakage current, thin window thickness, high doping concentration in the contact layer, reduced temperature during the fabrication process.

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Discussion

CAMPBELL: You claimed that the ^{60}Co peak was gaussian. At what fraction of the full height does it deviate from gaussian on the low energy side?

HERZER: Down to about 1%.

BERNT: Have you got an explanation for the small slope of capacitance with bias voltage? It looks as if you have got some series resistance in your detector.

HERZER: From the forward characteristics we know that low series resistances have been obtained. Thus the strange behaviour of the capacitance will not be due to this. We believe that probably surface channels will be the reason, since the capacitance was higher in these cases, than one should expect from the geometry.

FETTWEIS: We heard from the paper of Henck that trapping centers exist before the lithium-drifting in the germanium. Is it correct, that no such trappings exist in high resistivity intrinsic material?

HERZER: In our detection characteristics we did not see any trapping effects. Thus, you are right when you say that no trappings exist in this high purity material. In particular, we have demonstrated that no trapping centers have been created during our fabrication procedure.