

EVALUATION OF HIGH-PURITY GERMANIUM BY  
PULSE MEASUREMENTS ON DETECTORS

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EVALUATION OF HIGH-PURITY GERMANIUM BY  
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SUMMARY

Evaluation of high-purity germanium exhibiting acceptor concentrations in the  $10^9$  to  $10^{10}/\text{cm}^3$  range taxes normal methods of measuring semiconductor material parameters. It has proven difficult to obtain unambiguous measurements by the Hall Effect or conductivity methods. We show that pulse measurements on guard-ring radiation detectors fabricated from high-purity germanium, when properly interpreted, can provide data on acceptor and hole concentrations as a function of temperature that supplement data obtained by Hall Effect and conductivity methods.

The method, which is an extension of the technique used for detector capacity measurements, employs injection of electrical pulses via the detector into a charge-sensitive preamplifier. The shape and size of the output pulse permits determination of the characteristics of the depleted and undepleted regions of the detector; variation of the applied detector voltage allows choice of the relative thickness of the two regions. Results of measurements on two germanium crystals, over a broad temperature range, will be presented.

INTRODUCTION

Measurements on high-purity germanium  $p^+n^+$  diodes (radiation detectors) at 77°K provide a sensitive determination of several important semiconductor parameters; these include type, concentration and distribution of impurities. Since detector performance is very sensitive to trapping, extremely small concentrations of deep-level impurities can be detected. Considerable information of this nature has been accumulated from measurements on over 100 high-purity germanium radiation detectors.<sup>1</sup>

Conductivity measurements over a large temperature range provide additional information about the activation energies of the electrically active centers. A major difficulty in these dc-conductivity experiments is the production of demonstrably good ohmic contacts. A very convenient method, combining conductivity and detector experiments, uses pulse measurements on high-purity detectors. Only blocking contacts, which can be made at low temperatures, are

needed. The method is sensitive in the interesting temperature region, where the deionization of the electrically active centers occurs. Additional advantages of the method are the large information content in pulse-shapes, and the simplicity of pulse measurements.

EXPERIMENTS

Results of dc-conductivity measurements on a series of crystals have been presented in an earlier paper.<sup>2</sup> For the purpose of the present paper we will use some results from Ref. 2, corrected for temperature measurement errors. Our attention will be concentrated on two crystals, one showing a high acceptor concentration (#152), the other a low acceptor concentration (#153). The hole concentration-temperature relationship for a 1 cm thick full area slice of crystal #153 which contains over 2000 dislocations per  $\text{cm}^2$  is shown in Fig. 1. The slope of the deionization curve in the region near 14°K indicates that the material is partially compensated, and it cannot be described by a single acceptor level. Using the equation for a compensated semiconductor,<sup>3</sup> an acceptor level at  $\Delta E_A = 24$  meV above the valence band is derived from the slope of the deionization curve. From the net acceptor concentration  $N_A - N_D = 2.2 \times 10^9 \text{cm}^{-3}$ , and from one point on the deionization curve ( $p = 9.4 \times 10^7 \text{cm}^{-3}$  at 13.9°K was chosen), an acceptor concentration of  $N_A = 3.05 \times 10^9 \text{cm}^{-3}$ , and a donor concentration of  $N_D = 8.5 \times 10^8 \text{cm}^{-3}$ , were computed.\* The analysis of a similar measurement on a slice of the dislocation-free crystal #152 gave two acceptor levels, the first a  $\Delta E_{AI} = 83$  meV and the second at  $\Delta E_{AII} = 22$  meV. The slope of the higher-temperature transition can be described with the equation for uncompensated material,<sup>3</sup> and provides an acceptor concentration of  $N_{AI} = 4.4 \times 10^{11} \text{cm}^{-3}$ . The slope of the shallow-level deionization indicates compensation similar to crystal #153. An acceptor concentration  $N_{AII} = 5.6 \times 10^{10} \text{cm}^{-3}$ , and a donor concentration  $N_D = 1.2 \times 10^{10} \text{cm}^{-3}$ , were found. For reasons discussed elsewhere,<sup>4</sup> we conclude that the shallow acceptor level is probably produced by di-vacancies, while the deep acceptor level is due to vacancy

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† Presently working with grants from Janggen-Pöhn and Max Geldner Stiftungen and the Kanton Basel-Stadt, Switzerland.

\* In case the reader becomes lost in the details in this paper, he should at least note these values. They represent rather pure material!

clusters. The deep level was first observed and interpreted by Hall and Soltys.<sup>5</sup> They derived a activation energy of 79 meV, with a sensity of  $4.0 \times 10^{11} \text{ cm}^{-3}$  in considerably less pure material.

That these results are not influenced by contacts can be demonstrated by measuring the conductivity of the undepleted material in a partially depleted  $p^+\pi n^+$  high-purity germanium detector. The equivalent circuit of such a detector is presented in Fig. 3.<sup>6,7</sup> If the detector is connected to a charge-sensitive preamplifier, a unit voltage step fed through the  $p^+\pi n^+$  diode produces an output pulse equal to the quantity:

$$\frac{C_d}{C_f} \left[ 1 - \frac{C_d}{C_u + C_d} \exp \left( - \frac{t}{R_u(C_u + C_d)} \right) \right]$$

with  $C_d$  = capacity of the depleted region of the detector.

$C_u$  = capacity of the undepleted region of the detector.

$R_u$  = resistance of the undepleted region of the detector.

$C_f$  = feedback capacity of the charge-sensitive preamplifier.

This relationship indicates that a prompt voltage step equal to  $\frac{C_o}{C_f}$  occurs at the output, followed by an exponential rise to a final level of  $\frac{C_d}{C_f}$ , where  $C_o$  is the geometric capacity of the detector

$$\left[ C_o = \frac{C_u \cdot C_d}{C_u + C_d} \right]. \text{ The time-constant } \tau \text{ equals } R_u(C_u + C_d).$$

For the determination of the resistivity of the undepleted material, the dependance of  $C_d$ ,  $C_u$  and  $R_u$  upon the reverse bias voltage  $V_r$  must be known. Under the assumption that the acceptor concentration is constant in the whole  $\pi$ -volume, we derive

$C_d = C_o \sqrt{\frac{V_o}{V_r}}$  for  $V_r \leq V_o$ , where  $V_o$  is the voltage required for total depletion. Since the series combination of  $C_d$  and  $C_u$  equals  $C_o$ , we find:

$$C_u = \frac{C_o}{1 - \sqrt{\frac{V_o}{V_r}}}, \text{ and } R_u = R_o \left[ 1 - \sqrt{\frac{V_r}{V_o}} \right],$$

where  $R_o$  is the resistance of the  $\pi$ -material detector bulk. Combining these relations with the equation for  $\tau$ , we find :

$$R_o = \frac{\tau}{C_o} \sqrt{\frac{V_r}{V_o}}$$

The time-constant  $\tau$  can be experimentally measured at different temperatures as a function of  $V_r$ . From these measurements,  $R_o$  can be determined, and the hole concentration can be calculated at any temperature. With our conventional preamplifier, practical limits for measurement of  $R_o$  are 1 k $\Omega$  and 50 M $\Omega$ . With modifications, both limits could probably be expanded by a factor between 10 and 100.

In Fig. 4 the electronic set up for the measurement is shown. Guard-ring detectors were used to avoid surface effects, and the guard-ring was held within a few millivolts at the potential of the central region. Figure 5 shows a typical output pulse of an undepleted detector. The prompt step and the exponential rise appear clearly. The exponential fall is due to the feedback network; it should ideally have a time-constant substantially longer than  $\tau$ . In Fig. 6, a series of output pulses at 20 $^\circ$ K and 9.5 $^\circ$ K is presented for different reverse voltages  $V_r$ . The fast initial rise is suppressed in these curves.

The deionization of the carriers in detector #153-4.8 obtained from such measurements can be seen in Fig. 7. From the slope of the curve, an acceptor level  $\Delta E_A = 21 \text{ meV}$  is derived. This result is in agreement with the values obtained from dc-conductivity measurements.

The  $n^+$  contacts on our detectors are made by lithium diffusion. At low temperatures, the resistance of these contacts increases due to the deionization of the Li donors. This effect can be seen in the pulse measurements. In Fig. 8, the slow pulse is due to a voltage step applied to the detector at 8 $^\circ$ K, while the faster pulse is produced when the input pulse is fed to a test capacitor connected to the input of the charge-sensitive preamplifier. From the rise-time of the detector pulse, we derive a contact resistance of approximately 1 k $\Omega$ .

Care must be exercised in interpreting depletion layer measurements in crystals exhibiting high concentrations of deep acceptor levels (crystal #152). In normal thermal equilibrium, these levels would deionize (i.e. recapture holes) in the 60 $^\circ$ K temperature range. This is the deionization seen in dc conductivity measurements. In a depletion layer, however, the population of free carriers is very low, and the occupation of acceptor sites by holes is reduced accordingly. Consequently, deionization does not occur until the temperature is reduced to a lower ( $\sim 35^\circ$ K) value at which any holes captured by the acceptor centers remain essentially firmly bound to the sites.\* Transient voltage/capacitance tests in the transition region from 70 $^\circ$ K to 35 $^\circ$ K can be used to observe the hole trapping and release processes.

Another effect observed in detectors with deep levels concerns trapping of charge produced by radiation. After forward biasing a detector at 8 $^\circ$ K, the traps are saturated, and the loss of radiation-induced charge by trapping is reduced substantially. This improvement in charge collection lasts for several minutes at 8 $^\circ$ K, assuming that the hole traps are 83 meV deep.

\* This effect is not to be confused with field induced detrapping.

## ACKNOWLEDGMENTS

We would like to thank R. H. Pehl for detailed information on high-purity Ge detectors, and many useful suggestions and discussions. R. C. Cordi assisted in the detector fabrication. J. Mayer and G. Ottaviani contributed valuable suggestions to the interpretation of the carrier-concentration temperature relationship of our high-purity germanium. J. Anderson constructed the mechanical parts for the helium cryostat. The principal author (E. E. Haller) is grateful to the Janggen-Pöhn and Max Geldner Stiftungen and the Kanton Basel-Stadt, Switzerland for their generous grants to support his work at the Lawrence Berkeley Laboratory.

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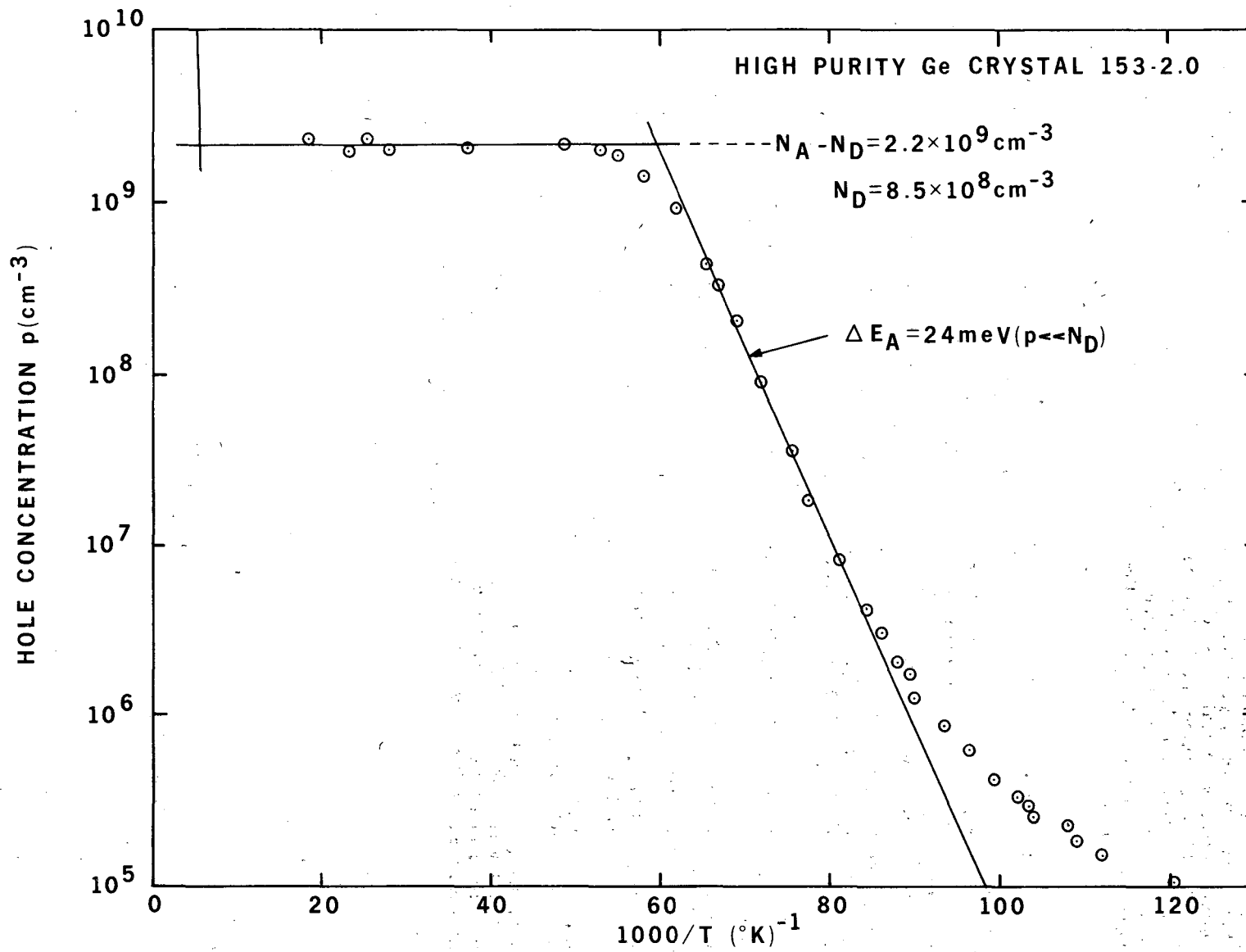
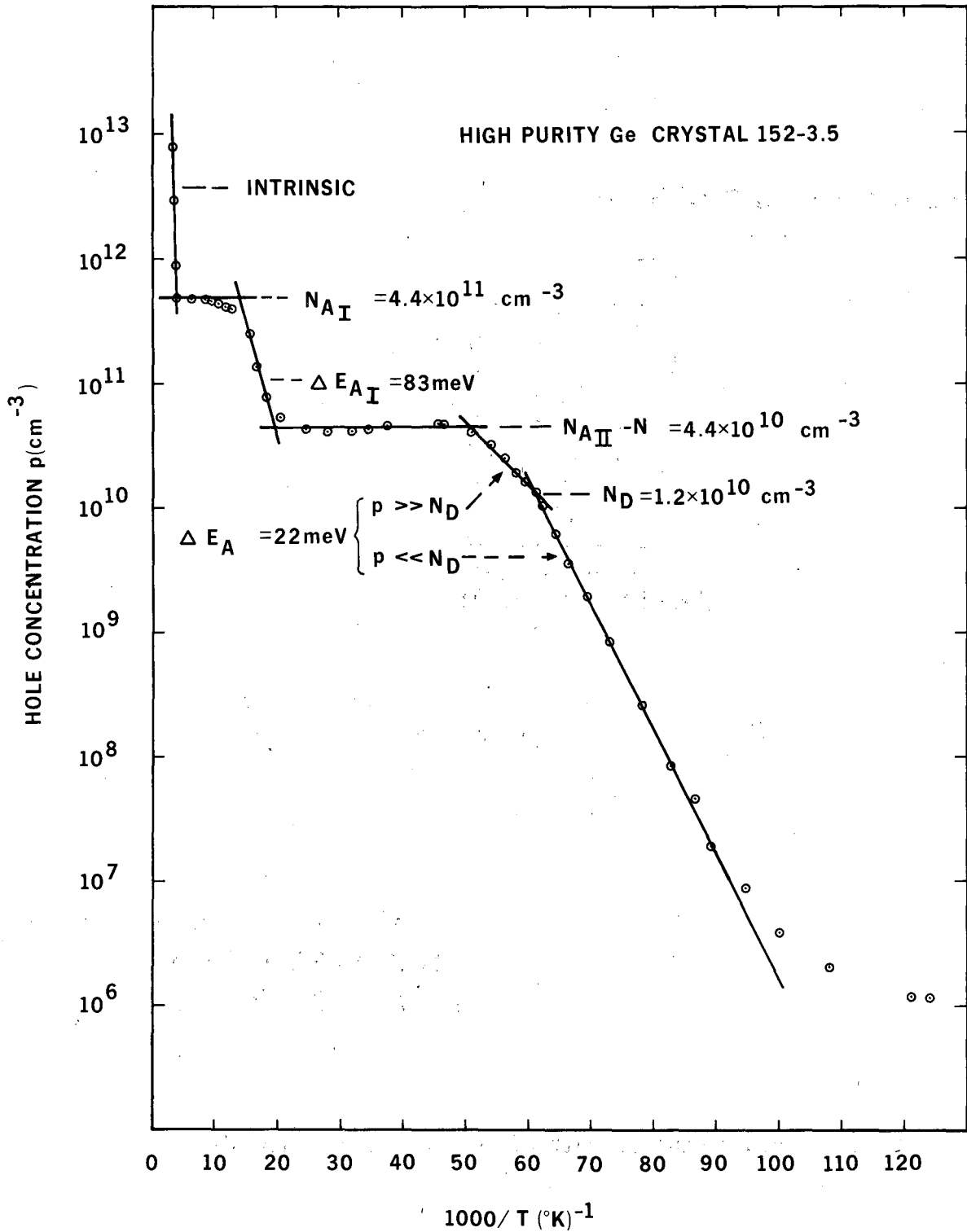


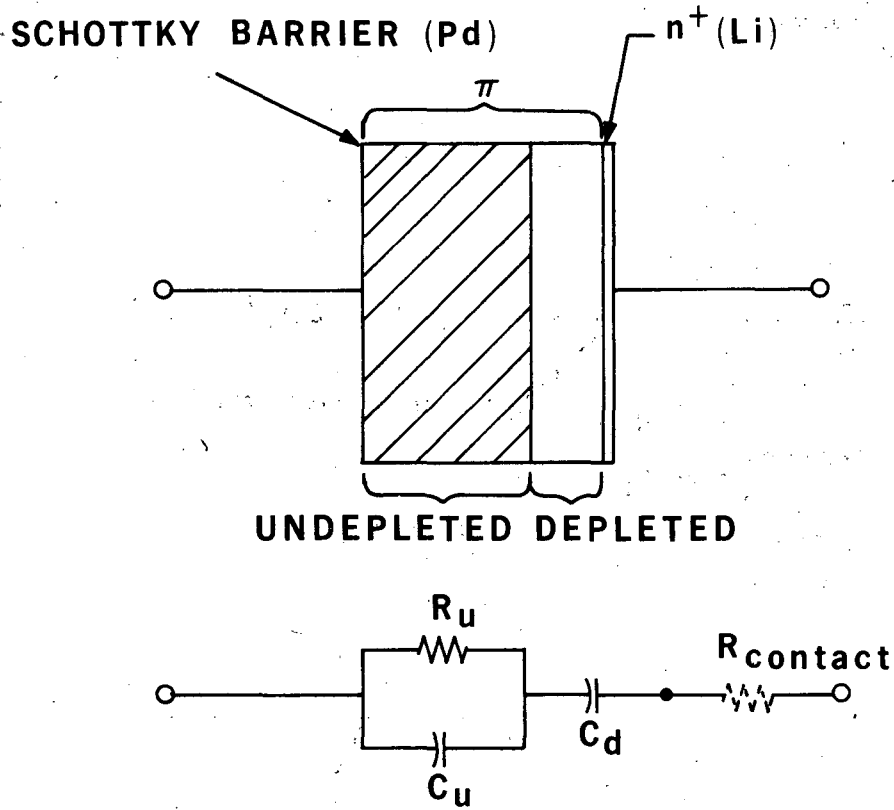
Fig. 1. Hole concentration vs. temperature determined from dc-conductivity measurements on a 1 cm thick, full area, slice of crystal #153. (4000 dislocations per  $\text{cm}^2$ .)

XBL 722-179



XBL 722-180

Fig. 2. Hole concentration vs. temperature determined from dc-conductivity measurements on a 1 cm thick, full area, slice of crystal #152. (Dislocation free.)



UNDEPLETED DEPLETED

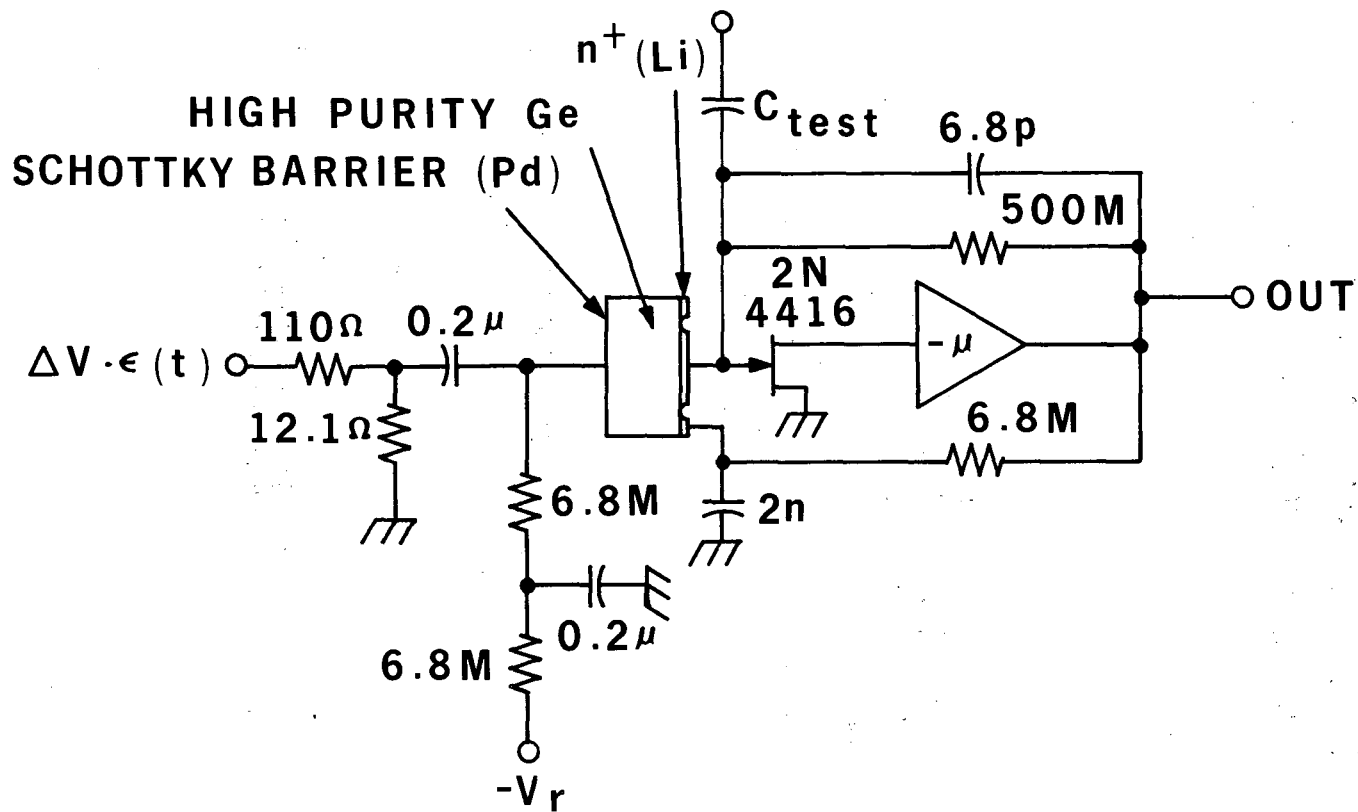
EQUIVALENT CIRCUIT OF AN UNDEPLETED HIGH PURITY Ge DETECTOR

XBL 722-178

Fig. 3. Equivalent circuit of an undepleted n<sup>+</sup>p<sup>+</sup> diode.



# CIRCUIT FOR PULSE MEASUREMENTS ON HIGH PURITY Ge DETECTORS

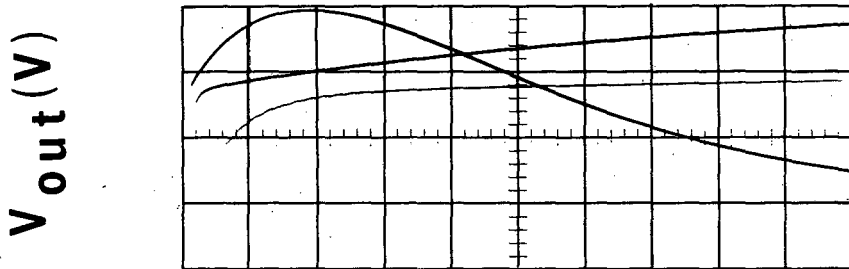


XBL 722-176

Fig. 4. Network for pulse measurements with undepleted high-purity germanium guard-ring detectors.

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# STEP RESPONSE OF AN UNDEPLETED DETECTOR

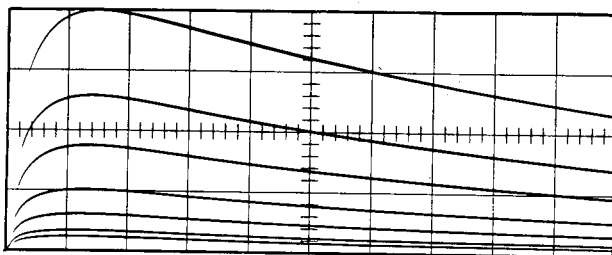


**TIME BASE: 0.2/2/20 $\mu$ S PER DIVISION**

Fig. 5. Typical output pulse response due to an voltage step applied to an undepleted detector.

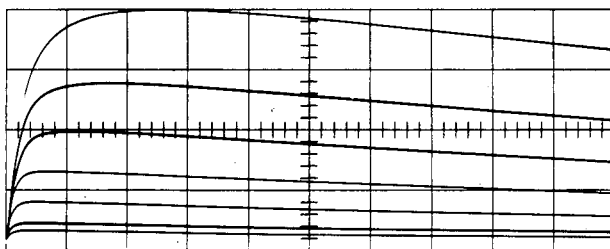
$V_r = 300/100/30/10/3/1/0V$

$V_{out}(V)$



$T = 9.5^\circ K$

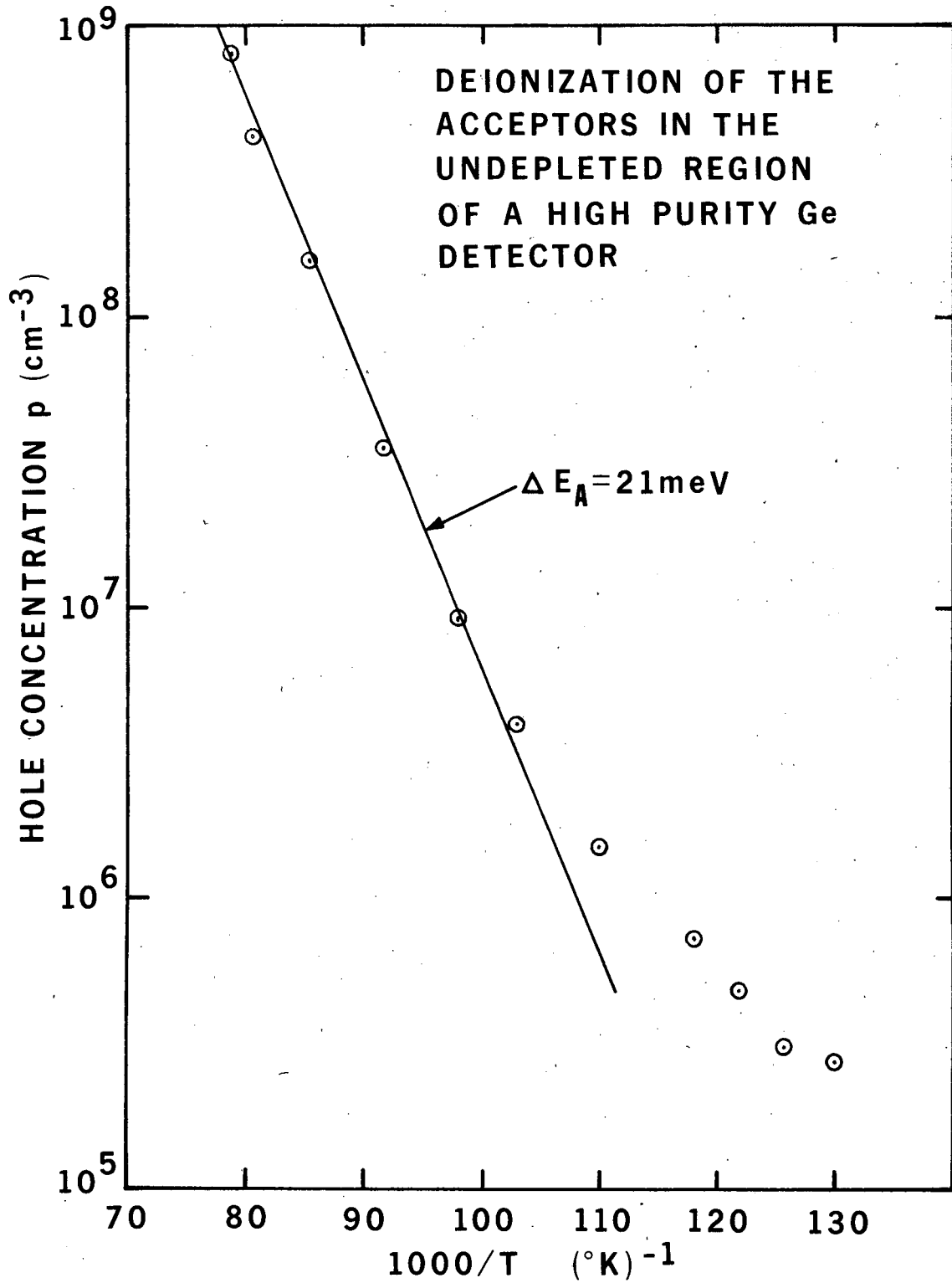
TIME BASE  $2\mu S/DIVISION$



$T = 20^\circ K$

TIME BASE  $0.2\mu S/DIVISION$

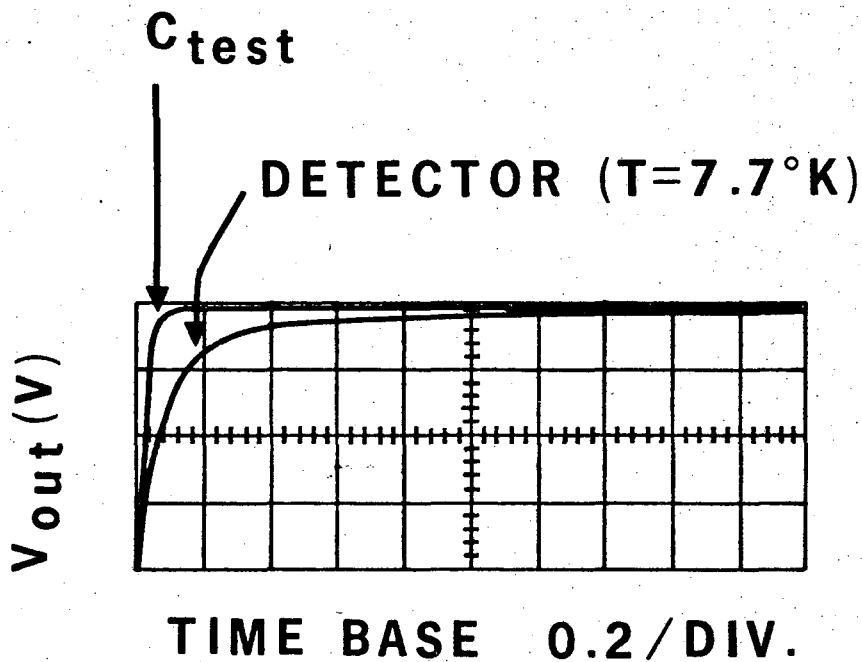
Fig. 6. Two series of output pulses at  $20^\circ K$  and  $9.5^\circ K$ . The reverse bias voltages are 300/100/30/10/3/1/0 volts.



XBL 722-175

Fig. 7. Hole concentration vs. temperature determined from pulse measurements on detector #153-4.8 (guard-ring detector: center diameter: 20 mm; depletion layer: 6 mm).

# EFFECT OF THE CONTACT RESISTANCE $R_{\text{contact}}$ ON $V_{\text{out}}$



XBL 722-174

Fig. 8. Comparison of two output pulses: the fast rise is due to a voltage step at a test capacitor, the slower rise is due to a fully depleted detector at  $8^\circ K$  and its contact resistance. The time-scale is 0.2  $\mu\text{sec}$ /major horizontal division.

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