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UCRL - 73494

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CON-720306-4

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HIGH OPERATING TEMPERATURE LIMITATIONS FOR GERMANIUM DETECTORS

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February 16, 1972

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This paper was prepared for publication in the
IEEE Transactions on Nuclear Science.

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HIGH OPERATING TEMPERATURE LIMITATIONS FOR GERMANIUM DETECTORS*

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Summary

The operation of germanium spectrometers at temperatures considerably in excess of 77°K (with attendant advantages in the cooling system) has been made possible with the advent of high purity germanium. The basic limitations on operating temperature are due to (1) increased trapping effects and (2) increased electronic noise.

An extensive analysis has been made of temperature-dependent noise sources. The principal limitation is due to trap and band-to-band bulk-generated currents. Experimentally determined parameters for germanium indicate that the operation of larger-volume detectors at temperatures in excess of 200°K is feasible. Several high purity detectors (1 cm³ and 14 cm³ in volume) have already been operated satisfactorily in the 170-180°K range, considerably higher than the 130-140°K maximum range observed for Ge(Li) detectors. In all detectors tested thus far, the principal limitation has been due to trap-generated current, which indicates the possibility of further improvement.

Introduction

The advent of high purity germanium has made possible germanium spectrometers that can be cooled only when operation is required and thus lend themselves to use in portable spectrometer systems. The complexity and efficiency of the cooling system depends on the minimum temperature required, and it is therefore advantageous to operate the detector at the highest possible temperature. This paper reports a study of the operating temperature limits of germanium detectors and relates these limits to the contributing noise sources within the detector.

Spectrometer Noise Degradation Sources

A germanium spectrometer system is limited by the following sources of noise or signal spread: preamplifier input noise, detector contact noise, charge generation statistics, charge trapping effects, internally generated detector noise, and signal variations due to temperature fluctuations.

Preamplifier noise is a function of the input electronics and the stray load capacitance and is independent of detector temperature. Detector contact noise can be minimized; it is not a controlling noise source. Charge generation statistics, while an important source of line spread, are not expected to vary significantly with temperature and can thus be treated as constant. Temperature fluctuations, while potentially a significant source of line spread due to the accompanying variations in average energy per generated ion pair, will not be considered since presumably sufficient temperature control can be obtained.

The remaining two items, charge trapping effects and internally generated detector noise, are both quite temperature sensitive. They will be considered in additional detail.

Charge Trapping Effects

Charge trapping effects are a major source of spectrum degradation at low temperatures for Ge(Li) detectors. Considerable effort has been expended on the problems associated with trapping and its effects.¹⁻⁵ In general, the degradation occurs due to charge loss in deep-level traps, which results in a net reduction in the signal. There is both a geometrical and a statistical variation in this loss, which results in a corresponding spread in the output signal.

Normally, the amount of charge lost is small and is of the order of $n_0(t_c/\tau)$, where n_0 is the original signal, t_c is the charge collection time, and τ is the mean time before trapping. Normally, germanium detectors are biased such that the charge collection velocities are approaching saturation ($\sim 10^7$ cm/sec). Thus, the charge collection times (t_c) are on the order of 10^{-6} d, where d is the depletion depth in centimeters. However, as the temperature is increased, carrier mobility decreases due to increased lattice scattering effects. Since increased fields are difficult to attain, this usually results in a decrease in collection velocity, and thus t_c increases. (For instance, at 300°K and $\bar{E} = 1000$ V/cm, $t_c \approx 10^{-6}$ d.) The increase in t_c causes a proportional increase in the charge loss due to trapping, with an expected worsening of detector performance.

There is, however, a compensating effect with increasing temperature. For a trap to be effective, the charge must remain trapped for a time longer than the shaping-time constant of the amplifier; otherwise, it could still contribute to the signal. Thus, if the escape rate from a trap becomes much less than the shaping time constant, the trap becomes relatively ineffective in producing degradation by charge loss. The mean escape time from a trap can be approximated by:

$$\tau_{ex} = \frac{1}{\sigma v_{th} N \exp\left(-\frac{|E_t - E_b|}{kT}\right)} \quad (1)$$

where

v_{th} = carrier thermal velocity ($\sim 10^7$ cm/sec)

N = effective density of states of either the valence or the conduction band

$|E_t - E_b|$ = trap energy difference from either the valence or conduction band edge.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

Fig. 1. Trap separation from the bandedge for an escape time constant of 10^{-6} sec as a function of temperature.

Figure 1 shows the required energy separation of a trap from the band edge as a function of temperature for a mean escape time of $1 \mu\text{sec}$. Values of σ were chosen to cover the range of expected capture cross sections normally encountered in traps in germanium. As can be seen, traps deeper than $|E_t - E_b| = 0.1 \text{ eV}$ at 77°K are effective. However, at 150°K $|E_t - E_b|$ must be $0.15\text{--}0.2 \text{ eV}$, while at 200°K $|E_t - E_b|$ must be $0.2\text{--}0.25 \text{ eV}$ to be effective as traps.

Thus, even though t_c increases with increasing temperature, resulting in a possible trapping increase, the effectiveness of a trap can also decrease and may more than offset the increase in t_c . This effect has been observed in at least one detector at LLL; a significant decrease in charge trapping degradation was noted for temperatures above 120°K .

Probably a more severe limiting effect of the increase in t_c is the required longer amplifier shaping-time constants. As will be discussed later, shorter shaping-time constants are desirable to reduce the flicker and the generation-recombination noise, but these cannot be used because of the increased detector collection times.

Internally Generated Detector Noise

The primary cause of the internally generated noise is the detector leakage current. A simplified approach in considering the noise due to this current is to assume a shot-noise characteristic.⁶ Estimates of the noise that would result for a leakage current of 10^{-9} A at $1 \mu\text{sec}$ shaping indicate a noise contribution on the order of 0.5 keV/nA . This is considerably in excess of measured values. As indicated by Hill and van Vliet,⁷ shot noise as such does not exist in semiconductors, since the origin and nature are different. Rather, the primary sources of noise are generation-recombination noise and $1/f$ (or flicker) noise. The primary source of the flicker noise is breakdown of the junction (usually surface breakdown). The generation-recombination noise occurs due to bulk current flow.

In general, we must consider the following sources of current in a PN junction:

- 1) Diffusion current. This source of current is due to the diffusion of minority carriers into the depletion region from the P and N contacts. The general expression for the magnitude of this current is

$$I_{\text{diff}} = Aq \left[\left(\frac{D_p}{\tau_p} \right)^{\frac{1}{2}} p_{n_0} + \left(\frac{D_n}{\tau_n} \right)^{\frac{1}{2}} n_{p_0} \right], \quad (2)$$

where

A = junction area

D = carrier diffusion constant

τ = carrier lifetime

p_{n_0} and n_{p_0} = minority carrier concentration.

- 2) Injected currents. These currents result from injecting contacts on the P or N junctions that inject minority carriers through the junction regions in a manner similar to transistor action. This current component is not uncommon in Ge(Li) detectors, but it can be readily controlled with proper fabrication techniques.
- 3) Photon generated currents. These currents are due to free carrier production by electromagnetic radiation. One of the more common sources is the $2\text{-}\mu$ infrared light emitted by the room temperature walls of the crystal.
- 4) Breakdown currents. These currents can be either surface or bulk in origin and usually result from locally large electric fields that cause avalanche breakdown. The breakdown process is quite noisy, and these currents dominate in limiting the maximum operating bias of a germanium detector at low temperatures.
- 5) Thermally generated current within the depletion region. This current is caused by thermal ionization of electron-hole pairs in the bulk—either by direct transition (band-to-band) or through traps (trap-generated).

The total current flow of a detector as a function of temperature and bias can be approximately represented by:

$$I(V, T) = I_0 + I_1 \exp(-E_g/kT) + I_2 V^\gamma + I_3 V^{\frac{1}{2}} \exp(-E_g/kT) + I_4 V^{\frac{1}{2}} \exp(-E_t/kT), \quad (3)$$

where

I_0 = photo-excited + injected currents (approximately a constant)

$I_1 \exp(-E_g/kT)$ = diffusion currents, which depend on temperature

$I_2 V^\gamma$ = breakdown currents, which have a strong bias dependence

$I_3 V^{\frac{1}{2}} \exp(-E_g/kT)$ = band-to-band generated current, which depends on temperature and the depleted volume (volume $\approx V^{\frac{1}{2}}$ until fully depleted)

$I_4 V^{\frac{1}{2}} \exp(-E_t/kT)$ = trap-generated bulk current.

The temperature-independent terms generally do not limit the maximum operating temperature. A possible exception may be in the breakdown current

term, since in many detectors the maximum applicable bias is found to increase with decreasing temperature. However, this is not a strong function of temperature (as compared with the exponential terms contained in the bulk-generated current sources). In addition, it is presumed that the voltage breakdown problem can be solved and hence does not represent a fundamental limitation on detector performance.

The remaining temperature-dependent terms involve the bulk-generated currents and the diffusion current. The existence of the diffusion current depends on the presence of lightly doped junctions that are in thermal equilibrium (i.e., the removal rate of carriers from these regions is much smaller than the generation rate within these regions). In practice, high purity detectors are normally fully depleted and have heavily doped junctions. As such, the diffusion current term is negligible. The importance of the diffusion current lies in its effect on analytical measurements.

The remaining temperature-dependent terms, then, are the band-to-band and the trap-generated current terms. The band-to-band current depends on direct atomic transitions. However, since germanium is an indirect band gap semiconductor, such transitions require a simultaneous phonon transfer. This decreases the transition probability significantly, so that current due to this source is expected to be small. The trap-generated current flow is expected to be the dominant current at elevated temperature and is thus of significant interest.

The trap-generated current flow essentially involves the transition rate of electrons into and out of trap levels in the forbidden bandgap. A generalized expression for the current due to a single trap is given by⁸

$$I = \frac{2V \sigma_n \sigma_p v_{th} N_t (N_c N_v)^{\frac{1}{2}}}{\sigma_n \exp[(E_t - E_v)/kT] + \sigma_p \exp[(E_c - E_t)/kT]} \quad (4)$$

where

V = depletion region volume

σ_n, σ_p = carrier capture cross sections

v_{th} = carrier thermal velocity

N_t = trap density

N_c, N_v = band effective density of states

$E_t - E_v$ = trap separation from valence band

$E_c - E_t$ = trap separation from conduction band

Usually the process is limited by the capture of one of the carriers. In this case, the current becomes

$$I = K \exp[-(E_t - E_v)/kT] \quad (5)$$

or

$$I = K' \exp[-(E_c - E_t)/kT],$$

where K and K' are lumped constants.

If the trap corresponds to a specific impurity or point defect, only one energy level (determined by

the charge state of the trap) is expected to dominate. In general, the levels closest to the center of the bandgap will be the most important, due to the exponential energy dependence. Current dependencies on temperature will take on the larger of the two exponential terms in Eq. (4), so that the slope should be greater than $E_g/2$. Slopes less than this probably result from generation through massive defect regions where other effects (such as field assistance) occur and Eq. (4) becomes invalid.

On the basis of the analysis thus far, it would appear that the operating temperature limitations are imposed by the bulk-generated current flow, since the remaining sources of current either remain approximately constant or else can be minimized. The principal source of bulk-generated current is expected to be through traps. Presumably, this source can be greatly reduced by judicious control of the quality of the starting material. Thus, the band-to-band generated current, which represents the true basic limitation on the upper operating temperature of the detector, is of definite interest.

Experimental measurements have been made on a number of detectors in order to validate the current-source model and to relate this to the observed noise within the detector. These will be discussed in the next section.

Experimental Results

It is important to determine the magnitudes of the various current components listed in Eq. (3). This can be done by taking reverse current vs bias and temperature data and then using the applicable temperature and bias dependence for each term to separate the components.

Most of the data were taken on high purity germanium detectors because of their relative stability and their potential application at higher temperatures. Plots of I vs $V^{\frac{1}{2}}$ (roughly the volume at biases less than that required for total depletion in high purity detectors) were made for a number of different temperatures. Figure 2 shows examples of the results for detector HP-6. Breakdown current contributions can be determined by the rapid current increase with bias at higher bias levels. At low bias levels, the current is characterized by a current intercept at zero volume. This intercept corresponds to the diffusion current plus any injected or photo-excited currents. The slope of the I vs $V^{\frac{1}{2}}$ curve is due to the bulk-generated currents.

The intercept currents, when plotted vs $1/T$, allow a separation of the diffusion current from the injected and photo-excited currents. Figure 3 shows the results obtained for detector HP-6. At higher temperatures, a very good fit with the diffusion current model is obtained if the lifetime in the P-region is 10^{-8} sec and the proper hole vs temperature values for the materials in this diode are used. The departure at lower temperatures is likely due to increasing experimental error as well as an increasing contribution due to injected and photo-excited currents.

Of potentially greater interest is the determination of the bulk-generated current that is found from the slope of the I vs volume curve. Figure 4 shows the results in terms of amperes per cubic centimeter for HP-6. At lower temperatures one observes an apparent trap-generated current with a slope of 0.23 eV, which is apparently due to excitation through a complex defect structure. At higher temperatures the current takes on a slope

Fig. 2. Examples of reverse current vs volume as a function of temperature for detector HP-6.

of about 0.7 eV; this represents the current due to band-to-band excitation. It should be noted that this was an exceptional diode. All other diodes had much larger generated currents per unit volume at any given temperature up to room temperature and did not exhibit the current slope of 0.7 eV. As a result, the band-to-band current indicated in Fig. 4 is felt to be an accurate measurement. At the worst it would represent an upper limit on the expected current due to this source.

The value of the band-to-band current is given by

$$I_{B-B} = 1.07 \times 10^8 \exp(-E_g/kT). \quad (6)$$

Due to the strong temperature dependence of this term, its magnitude becomes negligible at temperatures below 200°K.

Fig. 3. Diffusion current vs $1/T$ for detector HP-6 (data points). The line shows the computer diffusion current.

Additional reverse current vs $1/T$ data were taken on three other detectors. In these detectors, the diffusion current was not explicitly separated from the bulk-generated current. Instead, an upper limit on the diffusion current was estimated and plotted. In addition, the value of I_{B-B} is also plotted.

Figure 5 shows the volume-generated current vs $1/T$ for detector HP-8. As can be seen, this current is considerably in excess of the band-to-band generated current at all temperatures. At higher temperatures, there is apparently a contribution to the current by the diffusion current. Note that the diffusion current is also bulk generated. Since the remaining, undepleted detector volume was only about twice that used in determining the bulk generation, an increase in current by more than a factor of 3 is not expected. At lower temperatures, the current is exclusively trap generated and indicates a trap 0.4 eV from one band edge. The current at 200°K is more than 100 nA/cm³—more than two orders of magnitude greater than the band-to-band generated current.

Figure 6 shows the bulk-generated current vs volume for detector HP-11. In this detector, the undepleted volume was much greater, so the diffusion current played a more important role at high temperatures. In fact, a plot of diffusion current with $\tau_D = 100 \mu\text{sec}$ corresponds very closely to the measured current at temperatures higher than 200°K. Below this temperature, the current takes on a 0.28-eV slope, indicating a possible defect complex contribution. For all temperatures, the current is

Fig. 4. Thermally generated current density vs $1/T$ for detector HP-6.

Fig. 5. Thermally generated current density vs $1/T$ for detector HP-8.

Fig. 6. Thermally generated current density vs $1/T$ for detector HP-11.

well in excess of the expected band-to-band generated current.

Figure 7 is for Ge(Li) detector 116. In this case, the bulk-generated current is much larger than that expected for diffusion or band-to-band generated currents. Two discrete energies, 0.39 and 0.495 eV, are clearly seen. The 0.495-eV trap is expected on the basis of earlier observations on Ge(Li) detectors and corresponds to excitation through the lithium-defect trap that has been found to be the dominant electron trap in Ge(Li) detectors. In this detector, the trap-generated current is quite large; it is more than four orders of magnitude greater than the intrinsic band-to-band generated current at 200°K.

It is interesting to note that in all detectors except HP-6 the detector current at room temperature was controlled by trap-generated currents and in several cases was considerably larger than the expected band-to-band generated current. This has been noticed before in the case of Ge(Li) detectors, where there have been large variations in bulk leakage at room temperature with corresponding variations in the trapping properties of the detectors.

Computations of the expected current flow due to known discrete impurities can be made to get an estimate of the effect of different impurity concentrations on the observed current. The impurities chosen were Ni, Cu, Ag, Fe, and the O₃ oxygen complex. Since the capture cross sections depend on the temperature and charge state of the elements, it is difficult to know the proper capture cross section to use for both electrons and holes for these elements in the biased depletion region of a germanium

Fig. 7. Thermally generated current density vs $1/T$ for detector 116.

detector over the temperature range of interest. To a first approximation, coulomb attractive traps have an assumed cross section of 10^{-13} cm², neutral traps have a cross section of 10^{-15} cm², and coulomb repulsive traps have a cross section of 10^{-17} cm².

Figure 8 shows the expected volume-generated currents for Ni, Fe, Cu, Ag, and O₃ as a function of $1/T$ for a trap concentration of 10^{12} /cm³. The difference in slopes corresponds to the difference in energy levels corresponding to each impurity. Since the generated currents are proportional to the trap density, estimates can be made of the current contribution for different trap concentrations.

An estimate of the importance of trap concentration can be made for HP-8, where the slope is indicative of a deep level generation state. In this case, a trap concentration on the order of 10^{10} /cm³ will cause the observed current. This is quite a reasonable value for the likely impurity concentration in the original ingot. The detector current for detector 116 corresponds to a deep trap concentration on the order of 10^{12} to 10^{13} /cm³. Again, this is in keeping with the probable purity of the starting material for the Ge(Li) detector. The more shallow slopes result in rather high currents at lower temperatures for detectors HP-6 and HP-11, but these slopes do not fit the discrete level model, and corresponding impurity concentrations cannot be estimated.

It should be noted that the same traps are not necessarily responsible for current generation and charge carrier trapping effects. For instance, the properties of the O₃ complex are such as to indicate

Fig. 8. Predicted thermally generated current densities vs $1/T$ for the traps due to Ni, Fe, Cu, Ag, and the O₃ Complex for a trap density of 10^{12} /cm³.

its possible behavior as an effective electron trap in high purity germanium detectors. However, due to its small hole-capture cross section and distance from the valence band, it is a very poor current generator, as indicated in Fig. 8.

Detector currents at temperatures above 77°K, then, are primarily determined by the trap-generated currents. These currents, which vary greatly depending on the defect content of a given detector, normally are considerably in excess of the band-to-band generated currents, which represent the true limit on the high-temperature performance of germanium. Consequently, detectors destined for high-temperature performance require very careful trap control.

Prior to considering the noise properties of the detectors, it would be well to consider the V-I characteristics vs temperature for the two detectors on which noise measurements were taken.

The V-I characteristics for detector HP-6 are shown in Fig. 9, while those for HP-11 are shown in Fig. 10. In both cases, the high-voltage breakdown characteristics (i.e., current at a given voltage) are relatively independent of temperature above a given bias. At voltages below 1000 V for both detectors, a very strong dependence of current amplitude on temperature is seen, as expected, and it is in this voltage range that the previous reverse-current data was taken. At higher biases, detector HP-6 developed the excessive $1/f$ noise likely

Fig. 9. V-I characteristics as a function of temperature for detector HP-6.

associated with surface breakdown. Detector HP-8, however, did not show this tendency. Rather, the excess leakage tended to behave as generation-recombination noise, indicating that the source of this noise was possibly injection from the P^+ gold surface barrier contact. Work with this contact in the past has resulted in leakage currents less than 0.5 nA at 4500 V for this detector, but such V-I characteristics were not attainable for these measurements.

Due to the problem of breakdown noise at higher bias levels for HP-6, resolution data was limited to electronic noise and ^{57}Co resolution at 1000 V bias. Detector HP-8 was studied in considerably greater detail at higher bias levels due to the well-behaved noise that was observed. In addition, HP-8 had an active volume of 14 cm³, so that it provided interesting data on the high-temperature operating characteristics of a reasonably large detector.

Figure 11 shows the ^{57}Co resolution as a function of bias for detector HP-6 (active volume 1 cm³). As can be seen, quite reasonable performance was obtained up to 170°K, above which the noise started increasing due to the increased leakage current. Even at 180°K, the resolution was better than 5 keV and, in fact, was 2.6 keV at 180°K if a shorter shaping time constant (0.5 μsec) was used.

Figure 12 shows the electronic and ^{60}Co resolution for detector HP-8 (active volume 14 cm³). In this case, quite reasonable performance was obtained up to 160°K, above which the rapidly rising trap-generated current (which is shown as the dashed line) causes a rapid increase in noise. In general, the

Fig. 10. V-I characteristics as a function of temperature for detector HP-8.

degradation in resolution for this detector is due to the increase in electronic noise rather than a significant change in trapping properties. The slower-rising pulses, however, require longer shaping time constants, so a shorter shaping time constant ($\leq 2 \mu\text{sec}$) cannot be used here to reduce the low-frequency noise.

Figure 13 shows the electronic noise contribution as a function of measured leakage current. This data is of significant interest since it indicates the order of magnitude of leakage current that may be tolerated without excess noise. When this curve was plotted, no regard was given to the applied bias or temperature—only the noise properties of the current. On this basis, some scatter in the points is expected. A "noise slope" of 0.052 keV/nA was measured over the 0-200 nA range. This magnitude of noise is well below the 0.5 keV/nA estimate based on the shot-noise model. In fact, leakage currents in the 10-50 nA range are reasonable for a detector with an expected resolution of 4 keV at ^{60}Co .

The models that have been developed in the past for generation-recombination noise are primarily for semiconductor systems in thermal equilibrium. The depletion region of a detector is not in thermal equilibrium since the thermally generated carriers are quickly swept out by the high electric field. Therefore, the generation-recombination noise in the germanium detectors is primarily one of generation noise only. We can make a simple computation based on an assumed Gaussian variation in

Fig. 11. Resolution at 122 keV vs temperature for detector HP-6 for a bias voltage of 1000 V.

the rate of charge generation. For instance, 1 nA corresponds to about 10^{10} electrons/sec-cm². Therefore, $\sqrt{N} = 10^5$ electrons/sec-cm². For a shaping time constant of 2×10^{-5} sec, the standard deviation within the amplifier bandpass would be about 2 rms electrons, which corresponds to about 13 eV FWHM. Therefore, a noise slope of 0.013 keV/nA would be expected, which is not too far from the observed value of 0.052 keV/nA.

Certainly, the above calculation is greatly simplified. Extrinsic generation-recombination noise due to previously excited carriers being trapped and then reexcited also occurs. In general, the description of generation-recombination noise is complex and will not be considered further. One general observation can be made, however. Generation-recombination noise has a frequency dependence that depends on $1/(1 + \omega^2\tau^2)$, where ω is the frequency and τ is a carrier transition rate that is characteristic of the generation-recombination process. This type of noise, then, should be characterized by a low-frequency noise plateau followed by a high-frequency falloff in noise. The point of inflection in the frequency spectrum will depend, of course, on the value of τ . For trapping

Fig. 12. Resolution at 1.33 MeV vs temperature for detector HP-8 for a bias voltage of 3000 V.

time constants normally encountered in germanium detectors ($\tau_1 = 10$ -100 μ sec), falloffs are expected to occur in the 10^4 - 10^5 Hz range.

Noise frequency spectrum measurements were made on detector HP-8 both as a function of leakage current and bias. Figure 14 shows the effect of increasing leakage current on the noise frequency spectrum. Clearly, at low leakage currents the output of the preamplifier has a white distribution. As leakage current increases, a lower frequency noise, resembling a plateau, is seen to form; the magnitude of this plateau qualitatively corresponds to the leakage current.

Figure 15 shows the effect of changing bias at a given temperature. The higher bias condition corresponds to a somewhat increased noise level rather than to a sharp increase in $1/f$ noise that would be expected with the onset of surface breakdown. This corresponds to the earlier assumption that the increased current was likely due to contact injection at higher biases for this particular detector.

Fig. 13. Electronic noise contribution vs detector leakage current for detector HP-8. The amplifier shaping time constant is 2 μ sec.

Fig. 14. Effect of increasing leakage current on the noise frequency spectrum of detector HP-8 for a bias voltage of 1500 V. The leakage currents and temperatures are: (a) $I_R = 0.5$ nA, $T = 77^\circ\text{K}$; (b) $I_R = 14.5$ nA, $T = 140^\circ\text{K}$; (c) $I_R = 50$ nA, $T = 160^\circ\text{K}$; (d) $I_R = 120$ nA, $T = 170^\circ\text{K}$.

Fig. 15. Effect of increasing bias on the noise frequency spectrum of detector HP-8. (a) bias = 1500 V, leakage current = 220 nA, temperature = 180°K ; (b) bias = 3000 V, leakage current = 340 nA, temperature = 180°K .

Conclusions

It has been shown that the detector resolution performance can be directly correlated to the bulk-generated leakage current at higher temperatures and that this noise can be attributed to the generation-recombination noise process. While detector breakdown problems can be very troublesome, they can be minimized and do not present a basic limit for the high-temperature operation of a detector. Similarly, changes in the trapping properties of the detector have been shown to be minimal when compared with the detector bulk-generated current noise changes.

The basic limitation on detector leakage current is due to the band-to-band generated current, which is given by

$$I_{B-B} = 1.07 \times 10^8 \exp(-E_g/kT). \quad (7)$$

Based on the measured noise contribution of the leakage current, and if we assume a noise contribution limit of 1 keV as being tolerable, leakage currents of 20 nA are permissible. If a detector volume of 40 cm³ is assumed, then it should be theoretically possible to operate this detector at temperatures above 200°K with very good resolution.

In practice, bulk leakage currents are controlled by trap-generated currents and are well in excess of the band-to-band value in the 200°K temperature range. As an example, the current due to an estimated trap content of 10¹⁰/cm³ caused a leakage current of more than two orders of magnitude greater than the theoretical limit at 200°K for the 14 cm³ detector (HP-8) and limited the useful operating temperature to less than 170°K. Clearly, additional work on the deep trap content of germanium, which most affects current generation, is needed to further maximize the temperature of operation.

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