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INTRODUCTION TO LOW-NOISE PREAMPLIFIERS
FOR NUCLEAR SPECTROMETRY

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FOREWARD

This is one of a series of papers presented at the Gatlinburg Conference on Semi-Conductor Detectors and Associated Circuits (May, 1967). Taken together, the papers represent a general summary of some of the recent advances in this area at LRL, Berkeley.

INTRODUCTION TO LOW-NOISE PREAMPLIFIERS FOR NUCLEAR SPECTROMETRY*

By F. S. Goulding

1. Introduction

Apart from the detector itself, the noise performance of the first stage of signal amplification is the most important single parameter determining the energy resolution of a semiconductor detector spectrometer. Before considering details of the front-end, we will briefly mention other factors which enter into the system performance making both the measurement and direct comparison of results obtained by different groups difficult:

A. Amplifier Pulse Shaping Network

Any comparison between preamplifier resolution numbers given by different workers must take into account the type of shaping network used and the absolute value of its time constants. While it would be desirable to standardize measurements by use of a simple equal RC integrator-differentiator network, we must recognize that this network does not give the best resolution number and, human nature being as it is, workers consequently rarely quote results obtained with this simple network. Unfortunately, no universally applicable conversion is possible from results obtained in an experiment using one network to those which would be observed with another network, since the ratio of low and high frequency noise components depends upon the particular input amplifying device.

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Since the shaping network also critically affects the spread in output signal introduced by base-line fluctuations at high counting-rates, as well as by rise-time fluctuations in the detector signal, energy resolution performance of preamplifiers is best expressed using a simulated low-energy detector signal produced at a low rate by a pulse generator* having a very short rise-time compared with the time constant of the shaping network. If this is done, the resolution measured by the pulse method is in good agreement with the resolution calculated from an RMS noise measurement at the output of the amplifier. Since the RMS noise measurement is much simpler to perform, it is the most common method of measurement of the purely electronic contribution to system performance.

B. Noise Contribution from Later Stages

In quoting performance figures for preamplifiers, care must be taken to avoid noise contributions from later stages (or to correct for them). This generally implies carrying out the measurement with amplifier gain settings suitable for low-energy use.

C. Extraneous Noise (e.g., Microphony)

As we obtain better results, increasing emphasis must be placed on contributions due to microphony and other sources. It is easy to show that a change of capacity of 5×10^{-6} pF from input to ground will produce a charge equivalent to 100 eV of energy (in a Ge detector) if the input is at 1 V with respect to ground. The

*A word of caution is necessary here. Many pulsers, particularly the mercury relay type, produce pulses with a small inherent spread (<0.1%). We generally use a transistor chopper type of pulser for this measurement.

fact that mechanical resonances are usually in the 1 kHz region while our amplifier pass-band is in the 100 kHz region reduces the microphony effect by a factor of 100*, but the change of capacity required to produce significant degradation of resolution is still very small ($\sim 10^{-4}$ pF). We note also that the effect can be increased considerably if high voltages (e.g., 2 kV detector voltage) are present on components near the input connection. Moreover, many detector holders contain an excellent source of excitation for microphony in the boiling of the liquid nitrogen used to cool the detector.

The effect of microphony on the final measurement depends upon whether a pulse or RMS noise-meter method is employed, and, if a pulse method is used, the precise design of such elements as the dc-restorer preceding a biased amplifier or pulse-height analyzer can affect the result. Clearly every effort must be made to eliminate microphony before accurate noise measurements can be made.

2. Pre-Amplifier Configurations

Apart from the work of Radeka and Chase[1] on the parametric amplifier approach to low-noise amplification, all recent work has been concerned with the use of field-effect transistors. At the present time, there seems little reason to give further consideration to the parametric amplifier with its attendant complexity since its performance (despite a worthy effort on the part of Radeka and Chase) can be more than equalled by F.E.T. preamplifiers of conventional design. We will therefore consider only F.E.T. preamplifiers in the following discussion.

*Many amplifiers now employ pole-zero cancelling methods to achieve good high-rate performance. This boosts the low-frequency response and increases the effect of microphony.

A large number of papers has appeared dealing with F.E.T. preamplifiers. The earliest papers[2-4] described results obtained with F.E.T's at a time when commercial F.E.T.'s were at an early stage of development and the writers were elated to be able to improve somewhat upon the performance of vacuum-tube preamplifiers and then only when using selected F.E.T.'s. In mid-1965 a much improved F.E.T. became available commercially (initially the 2N3823, followed later by many types with similar performance) and subsequent papers[5-8] deal with the design and performance of preamplifiers using these transistors. We must immediately observe that the resolution results obtained are largely independent of the precise design of the preamplifier although certain other parameters, such as rise-time, high-rate performance, gain stability, linearity, etc., do depend upon the design. Resolution results depend more upon the lucky choice of a good batch of transistors from a particular manufacturer and the willingness of the preamplifier builder to engage in a long process of selection and optimization of F.E.T. conditions (particularly temperature). This has remained our position for almost two years. The minor advances made in this time are not the result of any major step in F.E.T. design and manufacture, but due rather to the dogged persistence of workers engaged in the selection process and the recognition of the importance of such parameters as temperature, microphony, etc. We hope this situation changes before too long, but we should bear in mind that it parallels a similar period of stagnation of almost twenty years with vacuum tube preamplifiers from 1946 to 1966. However, we should also recognize that the F.E.T. has made possible a 5:1 reduction in line widths at low energies in the past two years.

Two basic configurations are encountered in F.E.T. preamplifiers. The simplest configuration, used by Elad and Nakamura [(8)] uses the F.E.T. as a voltage amplifier with no feedback tothe input. In some cases, this group omits the bias resistor on the gate of the F.E.T. too, thereby reducing the stray capacity on the gate to an absolute minimum. Using essentially this configuration, R. Jared (LRL Berkeley [(9)] has achieved an X-ray resolution of 450 eV at low energies using a 1.2 pF lithium-drifted silicon detector. I believe that slightly better numbers have been achieved occasionally by other workers. Measuring the purely electronic contribution to this resolution is almost impossible in this circuit configuration and we will not hazard a guess at its value.

While the unfedback F.E.T. appears attractive for very low energy applications, gain drift problems and poor counting-rate performance limit its use to this specialized area. A much more satisfactory preamplifier for general applications uses a charge-sensitive feedback front-end. One example of such a unit is shown in Fig. 1. Similar designs exist in many laboratories and their resolution performance is almost the same. The best result we have obtained with a unit of this type is 260 eV FWHM electronic resolution with no added capacity*. The best X-ray resolution yet measured by us with a 1.8 pF silicon detector is about 400 eV FWHM*. We note that this is somewhat better than the unfedback unit's performance but this result occurs only due to the fortuitous choice of F.E.T.

*Both results obtained with a pulse shaping network containing a single 2μsec RC differentiator and two 2μsec RC integrators. Also note that these results are quoted for silicon detectors. Despite the apparent advantage of Germanium in requiring less energy per hole-electron pair, we have not quite equalled these numbers for low energy X-rays with any germanium detector.

Briefly, the preamplifier operates as follows:

The input stage F.E.T. Q1, drives a cascode (i.e., grounded base) transistor Q2 which is followed by emitter followers Q3, 4. Feedback is applied via R1 and C2 in parallel* to the gate of Q1. A charge impulse flowing through the detector is deposited on the feedback capacitor C2 producing a voltage step at the emitter of Q3. The charge on C2 decays via resistor R1. A large value of R1 is required if its resistor noise is not to degrade the overall performance significantly and a small value of C2 is required since it appears in parallel with input capacity as far as signal-to-noise calculations are concerned. The output of emitter-follower Q4 drives the operational amplifier stage and cable-driver containing Q5, 6, 7, 8, whose gain can be switched by a factor of 3 by means of switch S1. Transistors Q9, 10 act as short-circuit protection for the output stage. For high counting-rate and high-energy applications, the values of C2 and R1 are changed as described in another paper[10] presented at this meeting.

Fig. 1 also shows the provision to seperate the front-end stage from the remainder of the pre-amplifier. In all the systems discussed here, the F.E.T. and its associated components mount in the evacuated cooled enclosure with the detector. Temperature adjustment of the F.E.T. is accomplished by mounting a power Zener diode with the F.E.T. and coupling them to the liquid nitrogen cooled part of the system via a thermal resistance (about 200°C/watt).

*The values of R1 and C2 depend on the application of the preamplifier. For low capacity detectors, R1 will have a very large value (e.g., 5000MΩ) and C2 will be small (e.g., 0.5 pF). Higher capacity detectors generally use a larger value of C2 and smaller value of R1.

The F.E.T. temperature can therefore be optimized by choice of resistor R2 controlling the Zener diode current. The F.E.T. drain current is optimized by choice of R3. The best type of F.E.T. to use depends upon the detector capacity as discussed in the following paragraphs. As many high-valued resistors radically change value at low temperatures, it is desirable to maintain the feedback resistor near room temperature. To achieve this a heavy braid can be used for the feedback connection to R1, C2 and a very fine wire (nickel) from R1, C2 to the gate of Q1. A fine wire should also be used from the detector to R1, C2.

We note that dc connection of the detector to the F.E.T. is employed to reduce stray capacity to a minimum. Other advantages of this method of connection, which include less possibility of damage to the F.E.T., simple measurement of the detector capacity in situ and accurate measurement of the small detector leakage current are discussed in an accompanying pager.[10] These latter advantages were suggested originally by Radeka,[2]

3. F.E.T. Performance

In view of the intrinsic importance of the F.E.T. no introduction to modern preamplifiers would be complete without a discussion of the behaviour of the F.E.T. Prediction of the performance of an F.E.T. preamplifier can be made with the aid of the well known theory of noise in nuclear amplifiers (see, for example, reference No. 11) and Van der Ziel's [12] theory of F.E.T. noise sources. Using Van der Ziel's results it is possible to show that the equivalent noise resistance of an F.E.T. is given by:

$$Req = \frac{0.7}{g_m} \left(1 + 0.33 \frac{Cgs}{Ct}\right)$$

where Req = equivalent noise resistance

g_m = mutual conductance of F.E.T.

Cgs - gate-source F.E.T. capacity

Ct = total input shunt capacity (including Cgs)

For practical purposes we can simplify this equation into:

$$Req = \frac{1}{g_m}$$

We can then calculate curves like those in Fig. 2 showing the predicted variation of noise components as a function of time constant of the equal RC integrator-differentiator pulse shaper. The F.E.T. noise should decrease at longer time constants--as shown by the two examples, while the noise due to input circuit leakage current and input shunt resistance should increase at longer time constants. The F.E.T. curves in Fig. 2 are representative of the two main classes of situations encountered in nuclear spectroscopy. For use with low-energy X-rays, a very low capacity detector is used and a low capacity F.E.T. gives best results. One example is a UC150, which we assume to have a g_m of 10mA/V and input capacity of 5pF (including strays) at 77°K (which is the assumed temperature in Fig. 2). We see that, for a typical time constant, of 2.5μsec, the resolution due to the F.E.T. alone should be 80 eV (point A). Of course, if a detector is present in the circuit its leakage current and the feedback resistor* both contribute noise. Assuming 10^{-11}A and 5000MΩ, the actual operating noise point would be expected to be C, with about 180 eV total noise. This compares with our best result of 400 eV.

*The resistor is assumed to be at room temperature throughout this paper.

Considering the case of a higher energy application using a rather high capacity (10 pF) detector and an UC250 transistor as shown in the second line of Fig. 2, we see that the predicted F.E.T. noise might be 300 eV (point B). With a detector leakage of 10^{-10}A and 500MΩ shunt resistance, the operating point becomes D at 620 eV. A practical number to compare with this is 950 eV.

We see that the predictions are much better than the experimental results. However, it is interesting to examine the behaviour of predicted and experimental performance as a function of temperature. This is done for the UC250 case in Fig. 3. The measured performance of the UC250 generally improves as the temperature is reduced down to about 200°K then deteriorates at lower temperatures. At 200°K, the F.E.T. noise should be represented by point A and, taking into account the effect of detector leakage (10^{-10}A) and shunt resistance (500 MΩ) the noise point moves to B. Experimentally, point C is observed. The difference between theory (750 eV) and practice (950 eV) is not too large in this case. A bigger discrepancy is present at liquid nitrogen temperature.

These comparisons represent one approach to F.E.T. performance data. However, apart from invoking Van der Ziel's noise theory, we have neglected the internal mechanisms in the F.E.T. and their behaviour as a function of temperature. A few brief words must be said on this subject before closing this introduction. Experimentally a variety of characterstics are observed when we measure the behaviour of F.E.T.'s at temperatures between room temperature and 77°K. In most cases* the mutual conductance increases below room temperature, reaches a maximum, then decreases again at temperatures close to 77°K. The temperature of the maximum varies from 100°K to 250°K depending upon the type of transistor and the

*In some cases, the noise goes through two minima as the temperature decreases.

particular unit on test. A similar behaviour is seen in noise but the temperature of the noise minimum does not exactly correspond to the g_m maximum. In fact, no simply measured parameter seems to have any very direct bearing on the noise performance in our application.

One must question the total lack of agreement between theory and experiment for F.E.T.'s in high source impedance, low temperature uses. A likely source of the problem is the use of poor quality heavily doped (epitaxial) material for the channel of commercial F.E.T.'s. The behaviour of the mutual conductance at low temperatures suggests that impurity scattering might be responsible for reducing the rather large increase in g_m which would be expected at low temperatures. Surface effects are another likely source of noise, but in the better transistors, noise measurements as a function of time-constant indicate that this is not the major problem.

4. Conclusion

While semi-conductor detectors and their associated F.E.T. preamplifiers exhibit performance undreamed of only three years ago, there is clearly much room for improvement. This improvement is most likely to come from a better understanding of the noise mechanisms in F.E.T.'s and we hope that the later papers in the session throw some light on this subject.

References

1) V. Radeka and R. L. Chase, IEEE Trans. on Nucl. Sci. NS-3, No. 3, p477 (1966).

2) V. Radeka, IEEE Trans. on Nucl. Sci. NS-11, No. 3, p361 (1964).

3) T. W. Nybakken and V. Vali, Nucl. Instr. and Methods No. 32, 121 (1965).

References (Continued)

4) O. Meyer, Nucl. Instr. and Methods, No. 33, 164 (1965).

5) E. Elad, Nucl. Instr. and Methods, No. 37, 327 (1965).

6) T. V. Blalock, IEEE Trans. on Nucl. Sci. NS-13, No. 3, p457 (1966).

7) K. F. Smith and J. E. Cline, IEEE Trans. on Nucl. Sci. NS-13, No. 3, p468 (1966).

8) E. Elad and M. Nakamura, Nucl. Instr. and Methods, No. 42, 315 (1966).

9) R. Jared - private communication.

10) F. S. Goulding, D. Landis and R. Pehl, Design and Performance of a High-Rate System.

11) F. S. Goulding, Nucl. Instr. and Methods, No. 43, 1 (1966).

12) A. Van Der Ziel, Proc. IRE No. 51, 461 (1963).

Figures

1. Typical F.E.T. Low-Noise Preamplifier
2. Theoretical Performance of F.E.T.'s at 77°K
3. Predicted Performance of UC250 at Different Temperatures (Ct = 30 pF)

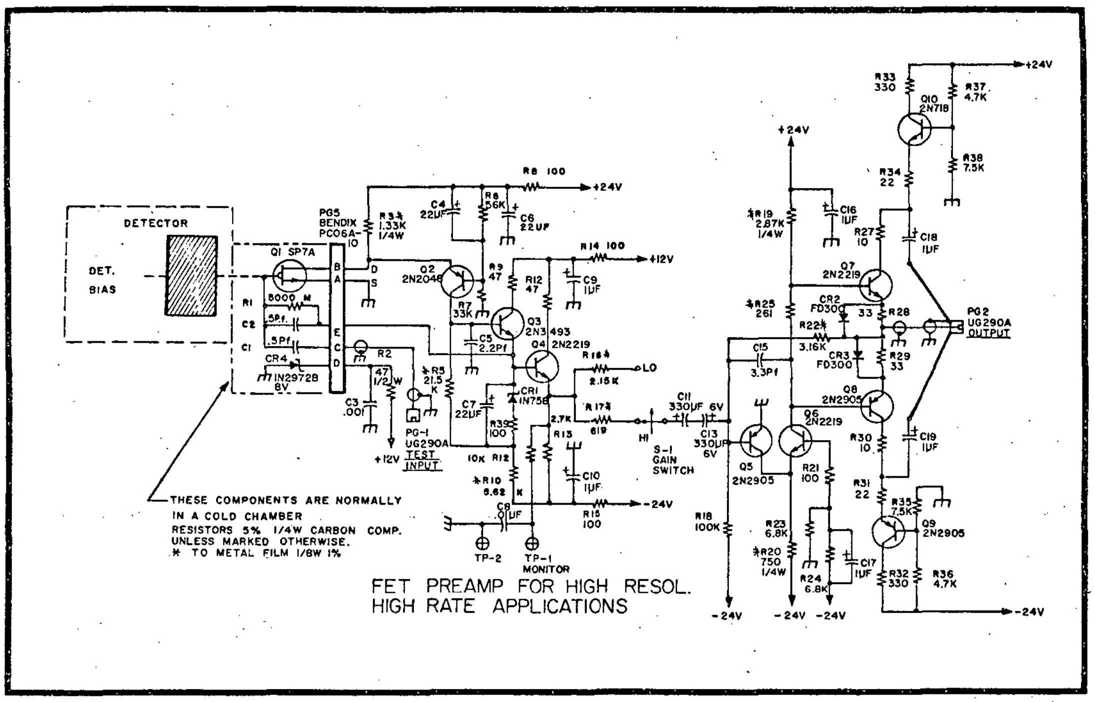
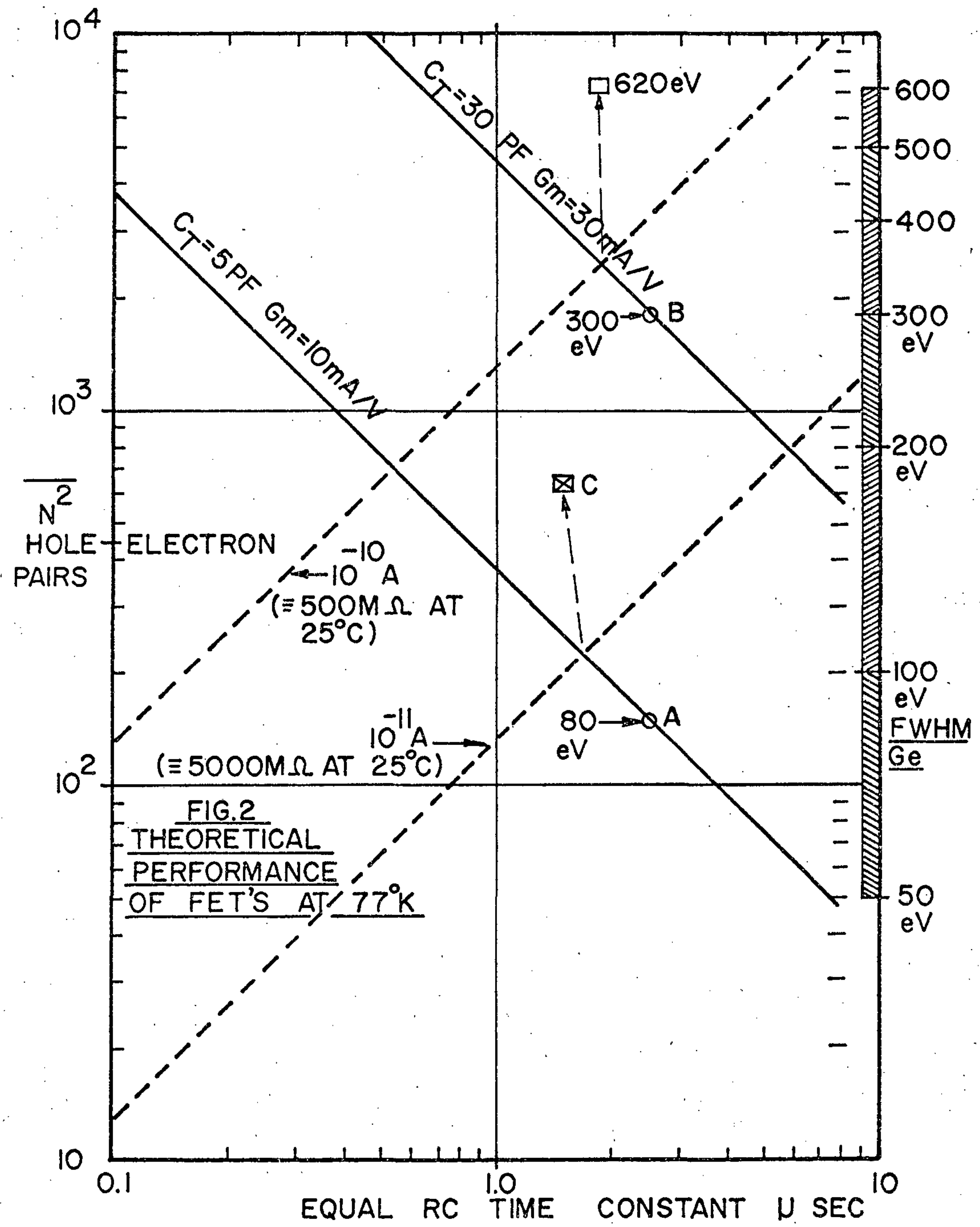


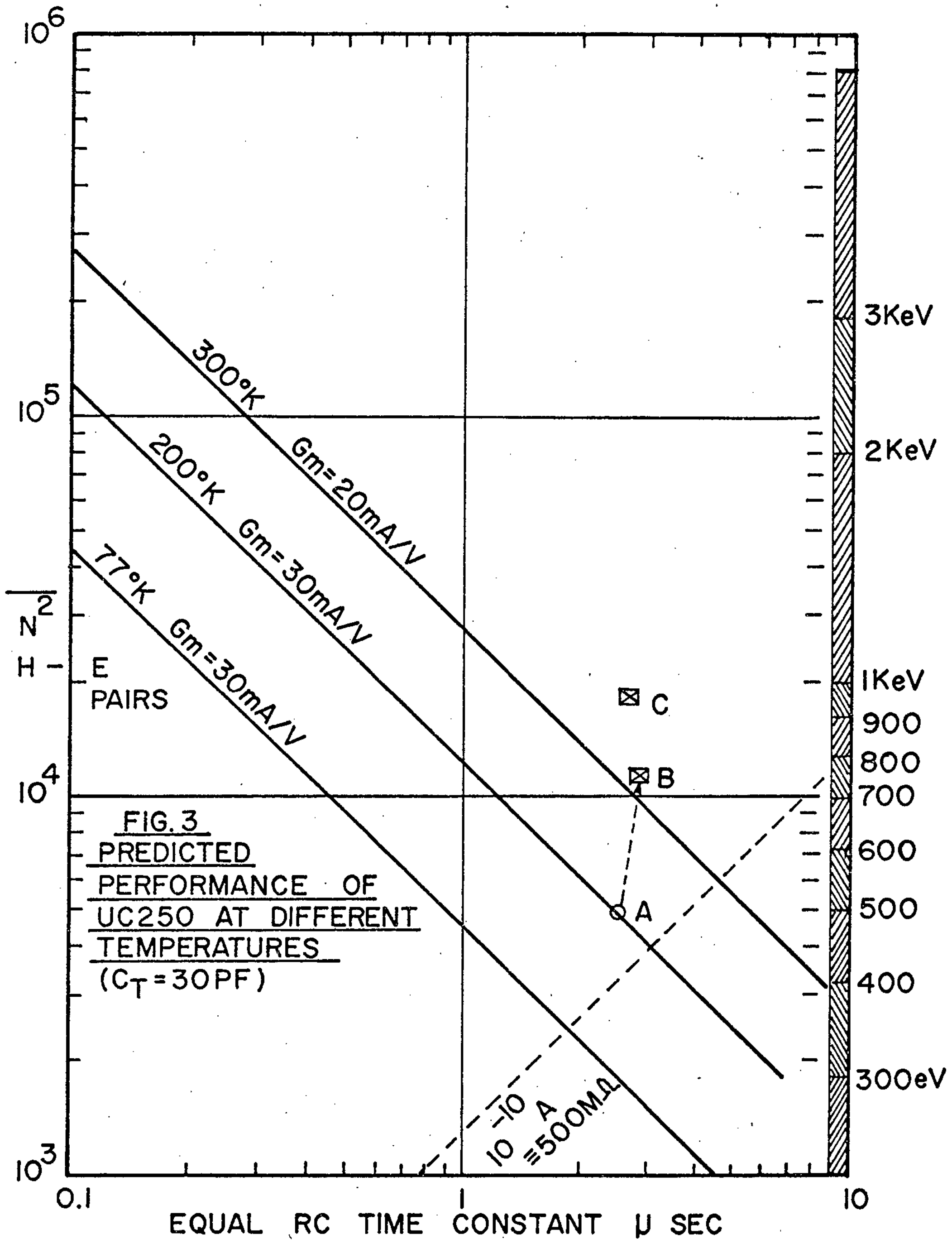
Fig. 1.

XBL 675-1460



XBL 675-1461

Fig. 2.



XBL 675-1462

Fig. 3.