FLUCTUATIONS IN SOLIDS

A symposium report by ***James J. Brophy***

THERE are an ever increasing number of topical technical conferences which supplement the general meetings of the various scientific societies. These gatherings, usually devoted to one quite specific research area, provide an opportunity for those scientists actively working in the field to concentrate on their specialty. However, they also increase the number of conferences one feels obliged to attend in order to keep abreast of current activities. That such meetings fulfill a purpose is attested to by the fact that many have grown over the years into formal conferences with attendances of several hundred.

The Fourth Annual Fluctuations in Solids Symposium held at Armour Research Foundation with the cooperation of the Office of Naval Research on May 5, 1960, was a topical meeting in which the subject matter, random phenomena in solids, was sufficiently restricted so that a completely informal atmosphere prevailed, allowing a maximum of round-table discussion on recent discoveries and current puzzles. The scientists attending heard no formal papers, but rather were able to engage in the type of give and take that seems to maximize the fruitful exchange of ideas. Such a conference requires an effective chairman to minimize chaos and R. E. Burgess carried out this task with complete aplomb.

The meeting began with experimental aspects of electrical noise in solids. H. Shenker discussed his latest work on prebreakdown noise in p-type germanium at liquid helium temperatures which confirms his preliminary results presented last year. The observed noise can be explained on the basis of a simple shot noise associated with the excess prebreakdown current. This picture confirms other studies which show the presence of current carriers having long mean free paths in the prebreakdown region. Furthermore, the work is illustrative of a shift in approach to noise studies in which noise is used as a tool to investigate the details of microscopic processes in solids, rather than as a phenomenon to be understood for its own sake.

Similar considerations motivated a detailed study of generation-recombination noise in single-crystal cadmium sulfide reported by J. J. Brophy and R. J. Robinson. These noise studies suggest the presence of trapping levels in agreement with those determined from thermally stimulated currents, and provide quantitative details about trapping and retrapping processes. Quantitative differences are observed in noise experiments under surface-absorbed illumination compared

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Participants, Fourth Annual Fluctuations in Solids Symposium. Left to right: J. J. Brophy, A. E. Attard, R. W. Estin, H. Shenker, H. Sommers, A. U. MacRae, G. Zaeschmar, H. C. Montgomery, R. J. Robinson, M. Lax, R. Fewer, M. S. Osman, W. Pagel, R. E. Burgess, J. E. Hill, K. van Vliet, L. J. Neuringer, W. Bernard (front), M. Epstein, P. J. Price, and H. K. Gummel.

to uniformly absorbed radiation showing the differences of the surface region compared to the bulk crystal. However, in both cases the same set of shallow trapping states is observed and these lead to trapping relaxation effects visible in the noise spectra.

In those crystals for which the trapping noise has a $1/f$ spectrum, Brophy is able to develop a semiquantitative description of the $1/f$ behavior in terms of trapping in distributed levels. A new relaxation effect, different from a trapping effect, is noticed in specimens which exhibit long-range photodiffusion when illuminated several millimeters from the electrodes. The characteristic time, 5×10^{-4} seconds, is thus attributed to with neutral diffusion in cadmium sulfide.

A major difficulty in completely understanding the noise in CdS is the absolute noise magnitude. The experimental results predict a value for the ratio of the variance to the average of the number of conduction electrons, $< \Delta N^2 > /N$, which varies from 10 to 10^4 depending on illumination intensity. Brophy and Robinson attribute this to retrapping and identify $< \Delta N^2 > /N$ with the number of times a photoelectron experiences retrapping before undergoing a recombination transition. This interpretation was severely criticized by M. Lax, K. M. van Vliet, and R. E. Burgess, each of whom was able to demonstrate that $< \Delta N^2 > / N \leq 1$, independent of trapping effects. In particular, Lax's general treatment is quite independent of any specific choice of trapping transition probabilities.

Similar measurements on lead sulfide under illumination in which the noise magnitude is in agreement with theory and hence $< \Delta N^2 > /N \sim 1$ were reported by van Vliet. A photoelectron may undergo several hundred trapping transitions, according to the noise measurements. The noise results may be understood on the basis of bimolecular recombination kinetics and this is in agreement with the observed response vs. radiation intensity behavior. Van Vliet observes that most investigators have reported that the response of PbS follows a 0.7 power law of the intensity, rather than 0.5 as expected from bimolecular kinetics. He shows that this is a result of examining the change in conductance versus intensity rather than using the proper plot of the difference between the squares of the total and dark conductances.

G-R noise in p-type InSb has also been observed by van Vliet. Previous studies of this material have reported no current noise. He finds the noise is measurable only in a very narrow (15°–20°C) temperature interval at the temperature for which the Hall constant is a maximum. At lower temperatures the high electron mobility reduces the noise in finite samples and at higher temperatures the carrier density is too great. Noise suppression due to degeneracy is negligible. By accounting for these factors, he is able to predict the noise level as a function of temperature which agrees with observations. Some $1/f$ noise is noted below 1000 cps at the noise maximum.

In another report of G-R noise in photoconductors, Shenker described work by himself and G. Picus on zinc-doped germanium. A plateau in the noise spectrum at 10^6 cps may be attributed to G-R noise and predicts an incident photon flux in agreement with responsivity data. Below 10^6 cps the noise increases, but not with a $1/f$ trend. The origin of this effect is unknown.

The $1/f$ noise in Esaki diodes was reported in separate measurements by H. C. Montgomery and H. Sommers. The short circuit noise current is observed to increase linearly with applied voltage right through the negative resistance region. This might suggest a surface leakage effect, but Montgomery found the noise level unaffected by change in ambient. Similarly, temperature effects appear to be small. Sommers' results show that units with good dc peak to valley ratios have lower $1/f$ noise than poorer diodes.

Relating the $1/f$ noise to excess valley current, Montgomery is able to plot the "true" diode characteristic, but obtains only fair results. It may be possible to improve this procedure by including high-frequency shot noise measurements which, as previously reported, are able to distinguish between forward and reverse tunneling currents. P. J. Price suggested that noise measurements may yield information about bound-state assisted tunneling and Burgess commented that Fröhlich's early work on shot noise suppression due to Fermi statistics may become important in these highly degenerate semiconductor structures.

From an analytical study of a semiconductor maser employing collisional ionization, Burgess is able to show that the device is not essentially more noisy than thermal noise in spite of the collisional ionization, which is usually considered to be noisy. However, he points out that in any molecular amplifier, consideration must be given to the discrete nature of the amplifying process and this may lead to an additional noise term proportional to the input signal.

A. U. MacRae described additional measurements on $1/f$ noise in high-resistivity germanium filaments using the field effect as reported last year. He has found that the noise level associated with a surface inversion layer increases three orders of magnitude upon reducing the temperature from room ambient to that of liquid nitrogen. In these experiments the inversion layer was produced by the field effect and was maintained constant with temperature. There appears to be an empirical correlation between the noise magnitude and the rate of surface relaxation back to equilibrium. MacRae points out that previous results showing $1/f$ noise to be independent of temperature may be due to the fact that the normal inversion layer is known to become smaller at low temperatures. These new results also show that the $1/f$ noise observed with an accumulation layer present is nearly temperature independent. The noise is much lower in this case, as previously reported.

The $1/f$ noise in diffused-base mesa transistors, which is orders of magnitude greater than in standard alloy devices, has been examined by H. Gummel, who finds that practically all of the noise appears to come from the emitter. A clever experimental technique is used to eliminate the difficulty that the base resistance couples the collector and emitter noise, making them difficult to separate. The separation can be effected by choosing the proper emitter current. From studies of devices having two collectors on opposite sides of the emitter, there is preliminary indication that the noise source is located at the emitter surface perimeter. R. Fewer finds that $1/f$ noise in grown junction *npn* silicon transistors at 1 kc greatly increases when an inversion layer is present and that some correlation exists between the noise level and the collector-base leakage current. Both effects are reversible, increasing and decreasing as the inversion layer is added and then removed.

The remainder of the session was devoted to theoretical considerations. Lax discussed his treatment of diffusion noise, which universally leads to a $f^{-3/2}$ power spectrum at high frequencies in one, two, or three dimensions. He also showed how trapping effects can be easily included and how trapping enhances the possibility of observing diffusion effects. Price suggested an alternative approach based on random walking which might be particularly appropriate for cascade trapping problems.

The ever present problem of the nonlinear *R-C* network was discussed from the thermodynamic approach by W. Bernard who related his work to that of Lax's statistical treatment based on the Markoffian assumption. The two approaches are not compatible, probably because they treat systems which are different in subtle fashions and neither may correspond to a real system. Lax commented that one cannot use a canonical technique because the macroscopic approach requires a departure from equilibrium and this is a contradiction.

Lax feels that the Nyquist approach must work but that the proper admittance must, of course, be used. The correct admittance is not that given by elementary circuit theory of a separately determined nonlinear resistance connected to a linear capacitance, a correction in the nature of an "interaction energy" must be included. Burgess remarked that this sounds suspiciously like the self-bias difficulty related to the unresolved question as to whether the average charge is zero or some finite value.

It seems clear from the discussions that not all subtleties of this deceptively elementary problem are clearly appreciated. The applicability of Nyquist's law was, however, universally accepted. This was, perhaps, the most appropriate note on which to close a conference on random phenomena. At any rate, at this point a nonrandom effect, the march of time, intervened and brought this year's meeting to a close.