# FLUCTUATIONS in SOLIDS

*By* ***James J. Brophy***

THE need for scientists to discuss informally their current research problems is illustrated by the well-known hall effect in operation at all formal society meetings. In those situations where the technical subject matter can be sufficiently restricted so that the attendance is small, it seems useful to bring such informal discussions from the hall into the conference room. Random processes in solids fits in this category and the Fifth Annual Fluctuations in Solids Symposium held at Armour Research Foundation on May 19, with the cooperation of the Office of Naval Research, provided an informal forum for a review of recent progress in this field. As in past years' sessions, no formal papers were presented and the subjects discussed were determined entirely by the wishes of the participants. Able chairmanship is needed to prevent such a meeting from descending into random chaos and R. E. Burgess was equal to this task.

Perhaps the most outstanding feature of this year's meeting was the sudden increase in the use of noise techniques to study the details of electronic transitions in semiconductors, particularly in germanium containing deep levels. The application of such crystals to far-infrared detection is well known and noise measurements make it possible to measure electronic transition probabilities to the deep levels, as beautifully illustrated by K. M. van Vliet who reported results of F. M. Klaasen on Ni-doped Ge. The thermodynamic theory of generation-recombination noise cannot apply to such double-acceptor situations because the existence of one level depends upon the occupancy of the other and this is excluded in the usual derivation. The results are in agreement with a more careful treatment, however, which van Vliet interprets to mean that the standard derivations are too restrictive. Also, the Shockley-Read theory doesn't apply to available crystals because the number of deep levels is not very much greater than the free-carrier concentrations, as is assumed in the theory, because of doping compensation. Fluctuations in carriers can be calculated directly from the well-known theory of generation-recombination noise, and the experimental results yield values for the various transition probabilities and cross sections.

A three-level model (valence and conduction band together with a discrete level) of G-R noise may be used to interpret such results, although the formally simpler two-level model is adequate in temperature regimes where the communication of the discrete acceptor level with the conduction band may be ignored. The variation of noise with temperature is very adequately explained in this picture as occupancy of the levels changes.

The difference between two-level and three-level effects is clearly shown by results described by J. Fassett on Mn-doped Ge at 77°K. The noise spectra in the dark show simple G-R noise with a characteristic frequency near $10^5$ cps, although the fall-off beyond the turnover is usually less than $1/f^2$, attributed to an inhomogeneous Mn distribution. Under infrared illumination of wavelength longer than $1.7\mu$, a second relaxation is visible in the noise spectrum with a characteristic frequency near $10^4$ cps. This arises from band-to-band transitions induced by the incident radiation. Under white light a $1/f$ noise spectrum is observed, presumably because of strong surface effects.

Two relaxations in the noise spectra of Au-doped Ge at 97°K are also observed by L. Neuringer and W. Bernard which can be interpreted in terms of a three-level model. R. L. Petritz described preliminary measurements on Cu-doped Ge undertaken to study the relative roles of thermal and room-temperature background-radiation generation of carriers. This is similar to work previously reported by G. Picus on Zn-doped Ge. Petritz's early results seem to imply G-R noise in excess of that expected.

Experimental techniques for such noise studies are not always simple, since the sample impedances are large in the dark at low temperatures, and noise data out to megacycle frequencies are sometimes necessary. Two-terminal specimens are used in some cases to make things easier, but then contact effects introduce uncertainties in the noise data. High $1/f$ noise levels at low temperature are felt by van Vliet to be a result of the difficulty in maintaining constant current conditions.

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Simple G-R noise in tellurium was discussed by van Vliet. The noise spectrum falls off as $f^{-1.5}$ because of carrier diffusion to surfaces, and $1/f$ noise is noted at low temperatures. Large G-R noise magnitudes in CdS and CdTe, so thoroughly discussed at last year's meeting, are interpreted by R. J. Robinson and J. J. Brophy in terms of trapping of the majority carrier, and are used to study $1/f$ noise caused by trapping. At this point the number of different materials which have been examined for G-R noise is getting large enough to require a summary and this is attempted in the table.

**Table I. Studies of General-Recombination Noise in Semiconductors**

| *Materials* | *Comments* |
|---|---|
| Ge, InSb, Te | Two-level model; quantitative agreement; yields minority carrier lifetime. |
| Ni-, Mn-, Au-doped Ge, PbS | Three-level model; quantitative agreement; yields transition probabilities. |
| Cu-, Zn-doped Ge | Three-level model; quantitative agreement not yet satisfactory. |
| CdS, CdTe, CdSe | Modified three-level model; accounts for large noise levels. |

Breakdown noise in In-doped Ge at 4°K was reported by H. Shenker as an extension of his previous work in the pre-breakdown region. In contrast to the pre-breakdown case which could be interpreted in terms of shot noise, nearer to breakdown the noise shows large irregular (though reproducible) variations with electric field. Some type of thermal instability or microplasma phenomenon seems indicated. H. Fritzsche described plans to examine current noise under impurity-conduction conditions using mechanical stress to split energy levels and change the noise properties.

Nyquist noise of hot carriers in germanium has been used by J. Gunn to measure their temperature with impressively elaborate experimental techniques. The transverse noise is determined during a five-microsecond heating pulse using lateral capacitive pickup probes and a 420-Mc gated amplifier. Constant current conditions are obtained using quarter-wave stubs tuned to 420 Mc in the current supply. Early results indicate a linear relation between carrier temperature and electric field. At 1000 volts/cm the indicated temperature is about 1000°K, with a crystal temperature of 77°K.

A. van der Ziel reported that noise in transistors at 77°K shows a large increase in the $1/f$ component compared to room temperature, and this accounts for some previous reports on noise in excess of shot noise at low temperatures. The location of the $1/f$ source has not yet been determined. His work on tunnel-diode noise shows simple shot noise for applied voltages less than that corresponding to the current maxima and $1/f$ noise at frequencies as large as 30 Mc for potentials

larger than that for the valley. Cooperative effects are suspected in this region.

The $1/f$ spectrum at subaudio frequencies in Ge, Si, and simple devices is under study by H. C. Montgomery using computer data-processing techniques to solve the considerable instrumentation difficulties at frequencies in the range $10^{-3}$ to 1 cps. The hope is to detect variations from $f^{-1}$ (or $f^{-1.2}$, which is observed) characteristic in the noise spectrum by determining the spectrum as precisely as possible. To date such variations as have been found are most often attributed to sampling errors in the data-processing scheme and to electrical- and thermal-drift processes.

Attempts to detect the influence of a surface electric field on excess noise in silicon, reported by W. Pagel, have run into experimental difficulties because of dielectric breakdown in the large fields required for silicon to change the surface conditions significantly. Some effect of the field on the noise seems to exist. Analogous experiments on CdS by R. Estin have shown no influence.

An attempt to extend the generalized Nyquist approach to nonequilibrium steady-state conditions was described by W. Bernard. The system-response function and the fluctuations are no longer simply related in this case, but several terms in the analytical expressions for each can be interpreted in simple cases. A peculiarity of the formal result is the presence of a temperature term, and considerable discussion ensued regarding the interpretation of temperature in a nonequilibrium state.

Polarization fluctuations in barium titanate, Rochelle salt, and triglycene sulphate at their curie points have been examined by J. J. Brophy. A thermal Barkhausen noise is detected in $BaTiO_3$ when the crystal is passed slowly through the curie temperature, but this disappears when the rate of drift is reduced to $10^{-5}$°C/second. TGS, which has a second-order transition, shows a noise peak down to rates of $10^{-6}$°C/second, and this may be the critical fluctuation effect predicted by Burgess. Quantitative interpretation of the data appears somewhat inconsistent, however, for the conductance component implied by the observed current-noise generator is much larger than suggested by other measurements. Brophy also described current-noise measurements on pyrolyzed polyacrilonitrile, an organic semiconductor, for which noise spectra similar to those observed in inorganic materials are found. Three relaxations are visible in the spectra, and these are relatively insensitive to pyrolysis-treatment temperature, even though the conductivity of the material changes considerably.

It always seems that in a one-day meeting such as this enough time may not have been allowed for complete discussion of any one point or set of experiments. Yet the new ideas received and the new awareness of other current activities attained adequately compensate for the modest time investment involved. Hopefully, the evidence that five such annual meetings have been held attests to their usefulness.