Fluctuations in SOLIDS

a report on the Seventh Symposium

By James J. Brophy

The seventh Fluctuations in Solids Symposium was held on May 22, 1964, at the University of Minnesota. Organized and hosted by A. van der Ziel and K. M. van Vliet, the informal one-day meeting again provided a forum for those actively working in the field to discuss recent results and resolve current questions. The previous symposium took place in 1962. This year's session was notable for its richness in diversity, ranging from laser noise to use of noise measurements to determine transistor *h*-parameters.

Appropriate to its recent emergence as a subject of interest, laser noise was first on the program and E. Wolf discussed aspects of fluctuations and correlations in light beams, while L. J. Prescott presented experimental results on noise in helium-neon lasers. Wolf reported recent work with L. Mandel and E. C. G. Sudarshan on the theory of light fluctuations.[1] He showed that the variance of the fluctuations of the photoelectrically counted quanta can be expressed as the sum of two terms, one being a particle effect, whereas the second term represents a wave effect (wave-interaction noise). This result is analogous to the well-known formula of Einstein in 1909 relating to the fluctuations for blackbody radiation. Wolf indicated how physical information may be obtained from a photoelectric analysis of light fluctuations. The wave-interaction noise terms were discussed for ordinary ("thermal") light and also for well-stabilized masers; in the latter case, this term is close to zero.

Prescott reported a strong correlation between the light noise and the current noise in a dc gas-discharge laser. The noise in the gas-discharge current modulates the number of excited atoms in the active part of the discharge and thus produces light fluctuations. Since only a part of the discharge participates in the laser action, the correlation is less than 100 percent.

Optical fluctuations are observed in the pale blue luminescence from MgO tunnel-emission cathodes of cold-cathode vacuum triodes. T. M. Chen reported on the experimental optical-noise spectra he measures in such tubes. The spectra are current-dependent and show much structure with a peak at 10^4 cps and a general increase at low frequencies. It is not yet possible to understand these spectra in detail, although qualitatively the fluctuations are attributed to random emptying of deep traps by the Zener effect in the high-field region, followed by luminescent transitions to these trap levels by electrons tunneling into the insulator from the metal substrate. From this picture, fluctuations in emission current are also expected because of the influence of trap occupancy upon the height of the potential barrier at the metal-insulator interface. Current noise is, in fact, present, and some correlation between the current-noise spectra and the optical-noise spectra is observed.

Similar effects are noted in the luminescence noise from a GaAs injection luminescence diode. J. J. Brophy described preliminary measurements comparing the forward current-noise spectra with the optical-noise spectra of a diode operated well below the threshold for laser action. Evidence for two characteristic time constants, 13 and 2.3 milliseconds, is apparent in both spectra. This is taken as evidence that similar carrier transitions are responsible for both the forward current noise and the optical emission noise.

The problem of temperature fluctuations and "shot" noise for heat flow was considered by R. E. Burgess. The thermal-equilibrium fluctuations in a homogeneous metallic conductor are

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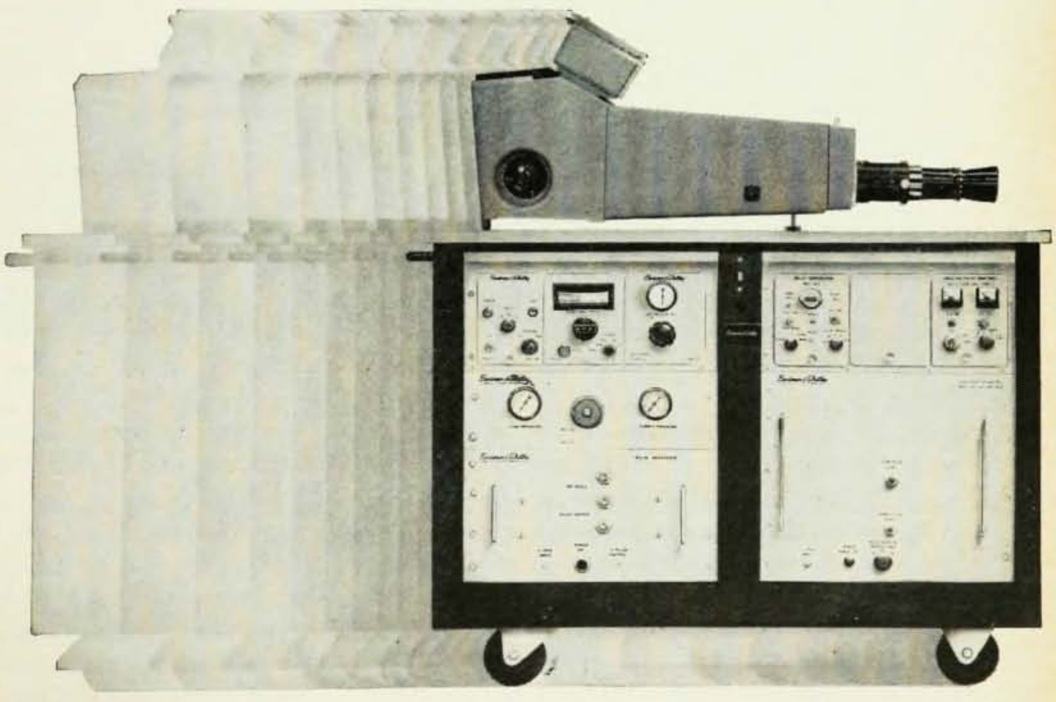

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calculated by two equivalent techniques: (1) by the use of series and shunt fluctuation generators associated with longitudinal and transverse heat transport, (2) by an extension of Nyquist's theorem to yield the cross-correlation spectra in terms of the thermal impedance and admittance matrices. It is then clear that the electrical terminations of the specimen influence the thermal fluctuations and vice versa. Such effects are often overlooked in standard transport calculations.

In nonthermal equilibrium with an applied electrical field and temperature gradient, it is found that the analog of shot noise for heat flow is derivable from a general statistical-mechanical treatment of the fluctuations of an arbitrary transported quantity Q. For electrical shot noise, $Q = -e$, while for thermal shot noise, $Q = mv^2/2$. The natural quantities to determine the auto and cross correlations of the electrical and thermal fluctuations are shown to be simply related to the Onsager coefficients. Consideration of possible experimental investigation in a nonequilibrium state shows that considerable difficulty can arise in attempting to separate quantitatively the effect of electrical and thermal fluctuations in a metal.

It is conceptually satisfying to develop the statistical distribution function of an extensive thermodynamic variable directly from statistical mechanical considerations. K. M. van Vliet pointed out that the standard approach of Boltzmann and Einstein using the microcanonical ensemble is not satisfactory since there exists, in principle, no possibility of fluctuations unless local nonequilibrium is assumed. Furthermore, the standard procedure involves an assumption of infinite reservoirs which is not applicable, for example, to calculation of semiconductor noise where the number of electrical carriers is finite.

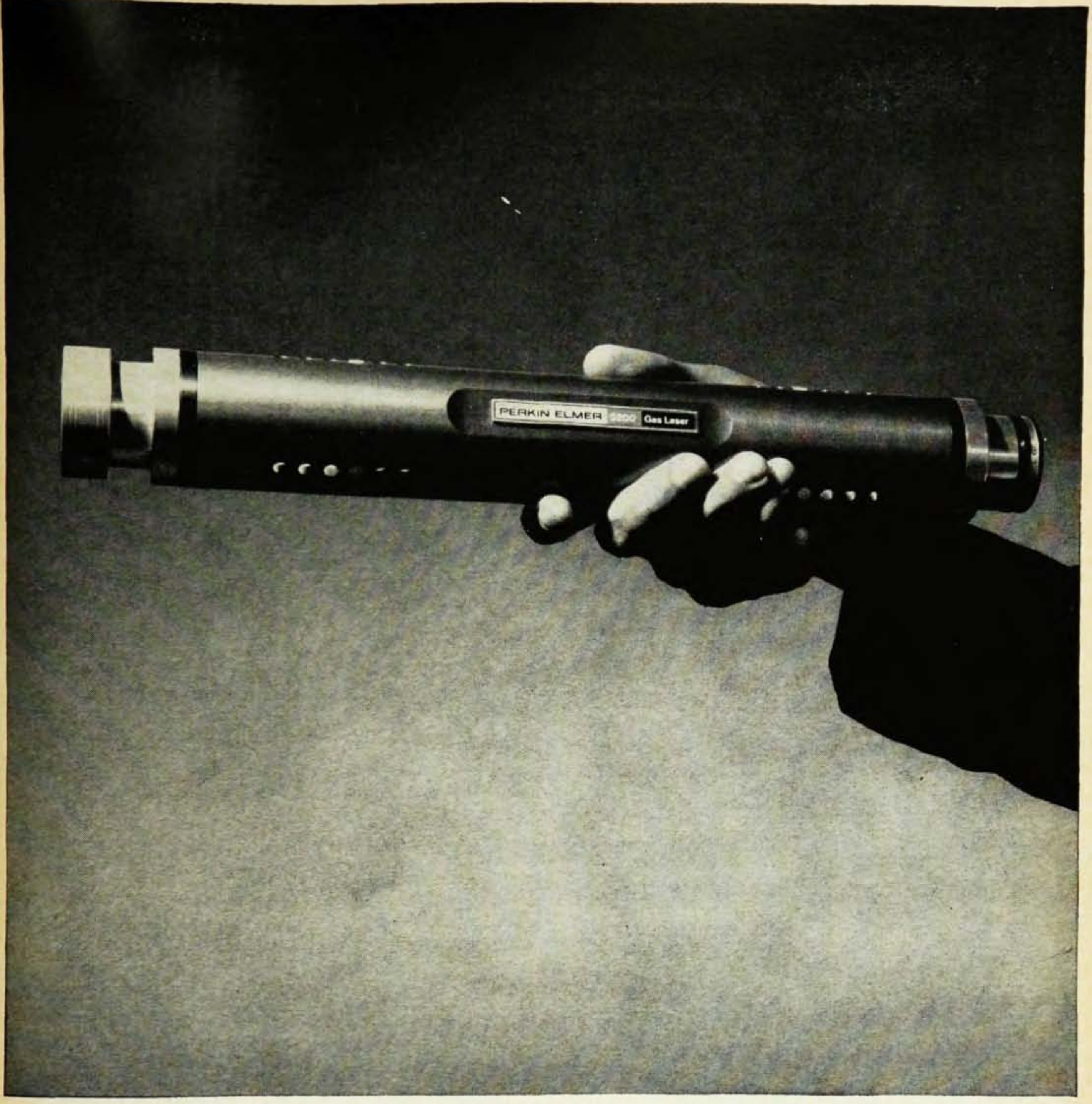
It is possible to remove the infinite reservoir restriction and to develop respectable results, as shown by van Vliet. A better approach is through the "thermodynamic ensemble" in which fine-grained fluctuations are allowed. It is possible to develop the distribution function, and, although the infinite reservoir problem is present again, it may be circumvented. A third attempt, using a nonequilibrium method to arrive at the distribution function through the master equation, also appears promising. Application of these ideas to fluctuations in solids has been made by van Vliet,[2] with emphasis on the multiple-level acceptor problem where the usual Fermi statistics do not apply since the two-electron levels are different from that of the one-electron model.

After the lapse of two years, it is perhaps surprising that the problem of giant fluctuations in CdS is still not completely understood. M. D. Pai has experimentally confirmed again that in some cases noise levels many magnitudes in excess of *g-r* noise can be observed in CdS crystals, while the noise-spectrum shape is more or less as expected. Significantly, however, he also has measured several samples for which the noise level is very low and equal to that given by theory. There is some indirect evidence that large noises may be associated with contact effects.[3] Conductivity modulation mechanisms near the metal-semiconductor interface are plausible explanations, but not yet understood.

The previously puzzling observation of large noise levels between Hall terminals (i.e., transverse to the current direction) on a semiconductor specimen has been quite satisfactorily explained by M. Epstein, who attributes the noise to the current redistribution accompanying local conductivity fluctuations in the body of the sample. In intrinsic specimens, the size of the local region within which conductivity fluctuations are assumed correlated is equal to four diffusion lengths. This model shows why Hall-terminals noise is large and also specifies the proper length-to-width ratio of a sample in which redistribution can be ignored, even with normal current probes (i.e., parallel to the current direction). It is possible, for example, to explain quantitatively negative noise correlations observed between adjacent regions of a wide sample on the basis of current-path fluctuations.

Other recent work on noise in materials is an extension of previously reported measurement of resistance fluctuations in the intermediate state of both hard and soft superconductors.[4] Lalevic now induces the intermediate state magnetically and finds, as before, discrete resistance levels presumably associated with metastable domain configurations. From the noise results, it is possible to measure the propagation velocity of growing and collapsing domains and to show that the speed is controlled by eddy currents. In deriving the energy condition for collapse, Lalevic finds that the collapse of a domain occurs longitudinally. One final word on materials was the contemplated experiments on the influence of neutron irradiation upon *g-r* noise in semiconductors by H. Bilger. He hopes to derive an improved understanding of the disordered thermal-spike region through the introduction and thermal anneal of Shockley-Read levels and the associated *g-r* noise effects.

The noise properties of field-effect transistors have proved to be a most fruitful area of study,



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with the result that even subtle details of the origin of noise in FET's are quite well understood, at least at intermediate frequencies.[5] Noise at high frequencies is less well in hand, although A. van der Ziel presented his latest approach, which involves setting up a wave equation for the voltage in the channel, thereby treating the channel as an active, nonuniform, distributed network. He is able to show that the upper cutoff frequency, where the noise begins to rise, can be made as high as one kilomegacycle if the channel length is as short as one-half mil.

Experimental measurements by W. C. Bruncke on practical FET's which have cylindrical geometry have been carried up to 30 megacycles. The results can be analyzed in terms of two ideal FET's in series and interpreted using partially correlated input and output noise generators. On this basis, good agreement between theory and experiment is attained.

Low-frequency FET noise, usually with a $1/f$ spectrum, is less well understood in detail. By studying noise at temperatures down to 64°K, M. Shoji shows that van der Ziel's theory involving thermal noise in the channel is adequate above 100°K. At lower temperatures, another trapping noise component predominates. Besides showing that this is a current noise effect, these results emphasize the importance of Joule heating in interpreting experimental FET noise measurements at low temperatures.

C. T. Sah interprets low-frequency noise as resulting from *g-r* noise caused by Shockley-Read transitions in the depletion region of the gate junction. The major noise source arises between the source and the pinch-off point and yields a noise level two orders of magnitude larger than similar trapping effects in the channel. These predictions are in agreement with experimental measurements by P.O. Lauritzen on gold-doped FET's and with the fact that neutron irradiation (10^{14} nvt) increases the noise by three orders of magnitude. The low-frequency noise spectrum of gold-doped FET's is a simple relaxation spectrum corresponding to trapping at a single gold level. The noise varies with temperature, just as simple *g-r* noise, and this is consistent with the lack of temperature sensitivity of the normal low-frequency FET noise (at constant current), if the $1/f$ noise is pictured as a distribution of elementary *g-r* relaxations.

It is significant that a simple relaxation spectrum is observed in these gold-doped specimens, whereas similarly doped bulk samples show more complicated spectra. Most likely, this is so because the active region in the FET case is deep inside the semiconductor, well away from disturbing surface effects. In addition, the active volume is quite small in the FET case compared to a bulk specimen, so that a greater percentage of the trap levels are in an identical environment. This means that the FET may prove to be a most useful experimental technique to investigate bulk noise phenomena under well-controlled conditions.

A similar comment can be made about the study of surface effects on noise through the use of insulated-gate FET structures, as described by C. T. Sah. He interprets noise in such units as resulting from random fluctuations in the surface-state occupancy at the silicon-SiO interface. Experimentally, $1/f$ noise is observed, except in gold-doped units having *n*-channels. The *p*-channel FET's usually have $1/f$ noise, even if gold-doped, although some structure attributable to transitions to gold levels is apparent. Thus, $1/f$ noise in these structures is not clearly understood; as van der Ziel points out, induced-channel units usually show a noise spectrum characteristic of a single time constant, while surface-state channels give $1/f$ noise. On the other hand, Sah calculates that even a discrete level can lead to $1/f$ noise if the channel length is taken into account because the variation of the Fermi-level position along the channel with respect to the trap depth introduces a distribution of relaxation times associated with one kind of level. Experimentally, insulated gate FET's are at least two or three orders of magnitude noisier at low frequencies than more conventional *p-n* junction structures.

Both suggestions, to use FET's in the study of single-level transitions and also $1/f$ surface noise, are in harmony with what developed to be a main theme of the meeting: the use of noise measurements to understand physical processes and to obtain results easily achievable in no other way. This is underscored by the use of noise measurements to measure the equivalent base resistance and alpha-cutoff frequency of high-frequency planar transistors by H. F. Cooke. Both parameters, difficult to determine by conventional techniques, are easily obtained from noise measurements, and agree with standard results where these can be had. Present high-frequency junction transistors show an upper noise corner at about 7 Gc caused by alpha falloff, and a lower noise corner at about 10 kc resulting from $1/f$ noise. Both frequency limits have improved recently as a result of improvements in fabrication processes and surface conditioning. Germanium units with a noise figure of one db at one gigacycle are

competitive with parametric amplifiers at this frequency, and the circuitry is less complicated.

Another example is the study of reverse breakdown current in Zener diodes discussed by P. O. Lauritzen. At intermediate frequencies (about 50 kc) and voltages, the observed noise is in agreement with simple shot noise corresponding to the junction Zener current. At higher electric fields, the noise increases, indicating the onset of avalanche breakdown. The transition from shot noise to avalanche noise proves to be the most sensitive means of detecting avalanche breakdown. The diodes studied were fabricated with a lateral impurity concentration gradient so that surface effects are negligible. In this connection, the fact that $1/f$ noise is detected at low frequencies is significant in showing, once again, that $1/f$ noise can be generated deep within a bulk semiconductor. Such diodes may prove equally useful as FET's in studying semiconductor noise free from disturbing surface effects.

Another type of *p-n* junction noise, described by J. J. Brophy, is useful in determining the spatial distributions of impurity ions near a *p-n* junction. The edge of the depletion region is moved periodically through the impurity distribution by means of a low-frequency reverse bias. With the junction at low temperatures, as the edge passes each impurity, a current pulse is produced and the sum of the individual pulses represents a noisy capacitive charging current. The experimental noise spectrum for silicon abrupt junctions is in general agreement with this simple model and suggests that the impurity atoms are not randomly distributed, but rather that a tendency toward clustering exists.

As is the case each year, the number of new ideas presented and techniques described is evidence for the far-reaching implications of fluctuation effects. These range from basic concepts of statistical mechanics to practical solutions of the problems of low-noise transistors. It is fortunate that a recent book[2] discusses a number of these in greater detail than can be presented in this short report. Many questions still remain, however, and all participants left eagerly awaiting another meeting next year.

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