Fluctuations in SOLIDS

By James J. Brophy

THE Sixth Annual Fluctuations in Solids Symposium was notable for the number of new random effects discussed, which is indicative of the ever-widening scope and application of noise phenomena. This one-day meeting on May 17, 1962, was held for the first time at the University of Minnesota and again provided an informal forum for those actively working in the field to discuss their most recent results and current problems. Co-hosts for this year's meeting were A. van der Ziel and K. M. van Vliet of the University of Minnesota, who succeeded admirably in organizing the random contributions of participants into a coherent program. Following the welcoming remarks by Dean F. Verbrugge, the discussions were arranged into four major areas: (1) noise in devices, (2) theoretical problems, (3) noise in materials, and (4) special topics.

The session on noise in devices showed how remarkably well the phenomena are understood in the better-studied solid-state devices and how rich in new effects are the noise phenomena in the newer devices. A description of noise in planar high-frequency transistors was given by H. F. Cooke. Because of their small accurate geometry and passivated surface, the noise figure of typical units is about 0.1 dB (for a 10^5-ohm source) from 50 cps to 50×10^6 cps. An increase in the noise figure at low frequencies is a result of $1/f$ noise, and at high frequencies of reduction in gain. In some units, the high-frequency 3-dB point is as high as 2×10^9 cps. Thermal noise in the base resistance contributes to the over-all noise level. The effect is frequency dependent because of capacitive shunting of the emitter junction and can be observed as a dip in the noise figure near 50×10^6 cps in silicon units and near 5×10^9 cps in germanium units.

A study of noise in field-effect transistors was reported for the first time by A. van der Ziel who attributes the limiting noise to thermal noise in the conducting channel. Because of noise modulation effects in the channel, the output noise is somewhat larger than thermal noise associated with the dc drain conductance. Predicted noise levels agree within a few percent with experimental measurements, which is highly satisfying and somewhat surprising, considering the early stage of the studies. Some field effect transistors show *g-r* noise at frequencies of 10^5 cps, and most units have $1/f$ noise below 100 cps. The possibility of induced gate noise generated in the input circuit by fluctuations in the channel, which is analogous to induced grid noise in vacuum tubes, has also been examined by van der Ziel. The magnitude of the effect has not yet been fully interpreted or observed experimentally.

Among the newer solid-state devices are those employing tunneling and shot noise in metal-oxide tunnel devices. These were discussed by R. J. Zijlstra, whose units were constructed by anodizing tantalum to produce tantalum-oxide layers 100 angstroms thick. Evaporated layers of either aluminum or gold are the second electrode. At low current densities (1 mA/cm^2), full shot noise is observed above 10^3 cps with a tendency toward $1/f$ noise at low frequencies. At larger currents, less than full shot noise is observed at high frequencies. This may be an equivalent-circuit effect, since the internal impedance has not yet been measured at these frequencies, but there is also some evidence for trapped charge in the insulating layer which might lead to shot-noise suppression. In other measurements, it is found that the $1/f$ noise component increases a factor of ten upon reducing the temperature to 80°K.

A calculation of shot noise for two-step tunneling in Esaki diodes has been carried out by P. J. Price. The results show that the observed noise may increase with frequency even if it is assumed that the trapped carrier is immediately available for re-emission. The observed noise, however, must always be less than or equal to shot noise. In a further analysis, Price has used a Brownian-motion treatment for the passage of the carrier from the as-trapped condition to the ready-to-be-emitted condition, introducing further frequency effects.

Zijlstra also described work on space-charge limited current noise in thin cadmium-sulfide single crystals. The noise-current spectra show simple relaxation phenomena having time constants identical with those observed in standard photoconductive *g-r*—noise spectra. In addition, there is evidence for a noise increase at about 10^6 cps because of space-charge transients similar to those previously observed in gold-doped germanium. This phenomenon occurs when the effective

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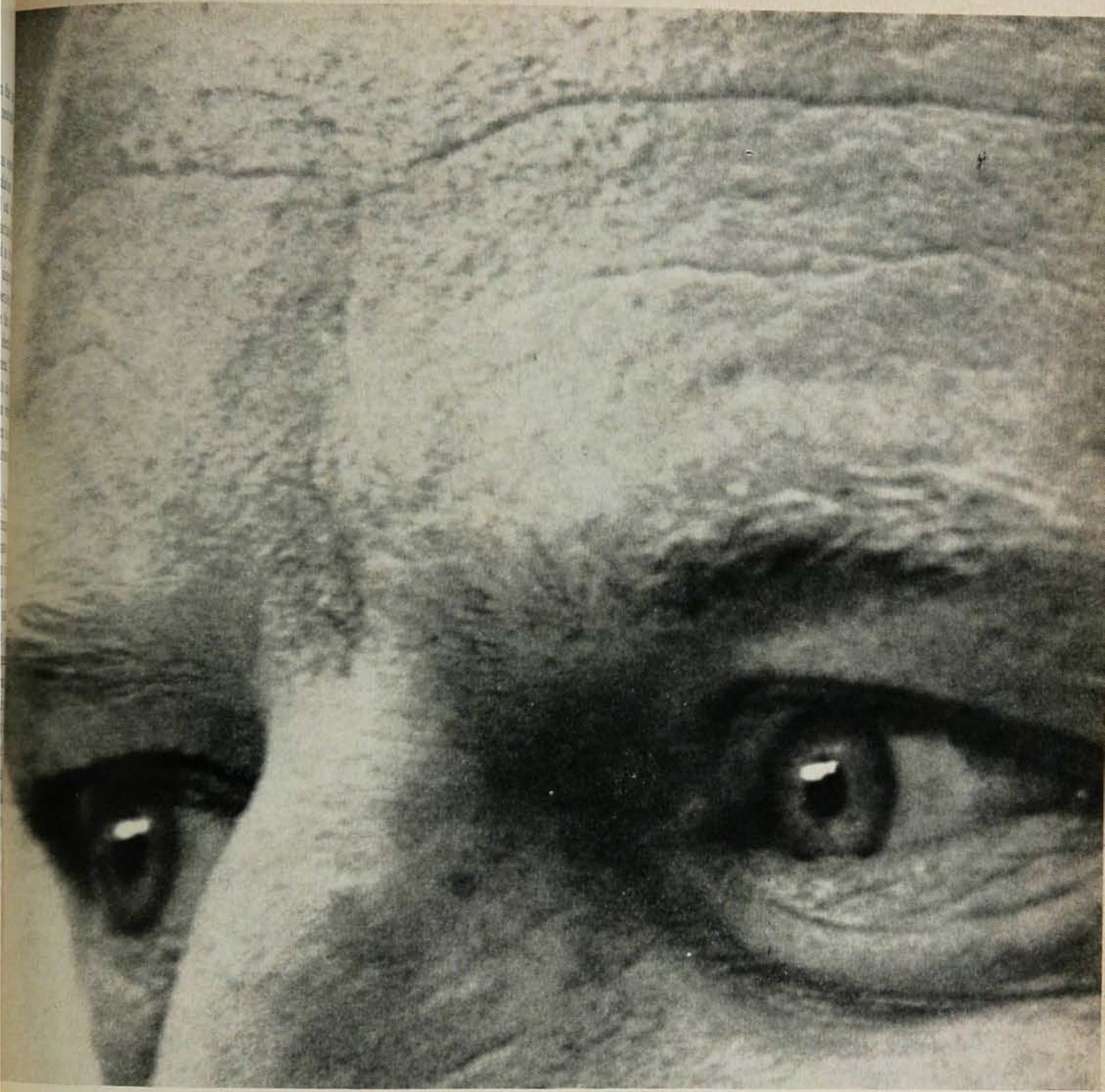
The theoretical segment of the program was opened by R. E. Burgess, who discussed the calculation of noise in semiconductor plasmas. He pointed out that the correlation function of the electric-field fluctuations at two different points in the plasma, expressed as functions of the wave number and frequency, has singularities which are identical with those of the dispersion relations. Since it may prove easier to calculate the correlation function, such singularities can be identified without direct knowledge of dispersion phenomena. The build-up in fluctuations near such critical points can be treated, using the generalized Nyquist relation with a proper effective temperature (when the system is not in equilibrium), which describes both the macroscopic and fluctuation properties.

In calculating the spectral density of particle fluctuations in a given volume in the presence of transport processes, the standard technique is first to compute an autocorrelation function in the time domain from which the spectrum is found with the Wiener-Khintchine theorem as the Fourier transform. This approach is usually mathematically complex and, as pointed out by J. R. Fassett, both steps are actually unnecessary. In general, the spectral density can be obtained directly from the Laplace transform of the Green's function for the macroscopic transport process, without transforming back to the time domain. With this technique, Fassett has solved one-dimensional diffusion, diffusion into and out of a spherical volume (Green's function for Helmholtz's equation), ambipolar transport, and diffusion from a volume into a finite domain. In the latter case, the spectrum has a low-frequency plateau, a frequency interval with an $f^{-1/2}$ behavior, and a high-frequency portion falling off as $f^{-3/2}$.

The study of fluctuations during return to equilibrium from a nonequilibrium state has been calculated by P. Gottlieb, using a pair-probability approach. Order-disorder theory in the time domain, rather than in spatial dimension, is used to determine the most probable path to equilibrium.*

Opening the discussion on noise in materials, M. Epstein reported that the problem of giant fluctuations in cadmium sulfide still exists. In agreement with previous measurements, his observed noise levels are many orders of magnitude greater than predicted by the standard steady-state *g-r* calculation, while the shapes of the spectra are as expected. In attempting to carry out a Hall-effect measurement in order to measure carrier fluctuations directly rather than indirectly from conductivity fluctuations, Epstein finds that the open-circuit noise voltage at the Hall terminals in the absence of a magnetic field is of the same magnitude as that observed across the current terminals. It proves impossible to balance out this transverse noise by any of the

* Cf. Kikuchi and Gottlieb, Phys. Rev. 124, 1691 (1961).



standard Hall balancing techniques, and the origin of the transverse noise is not clear.

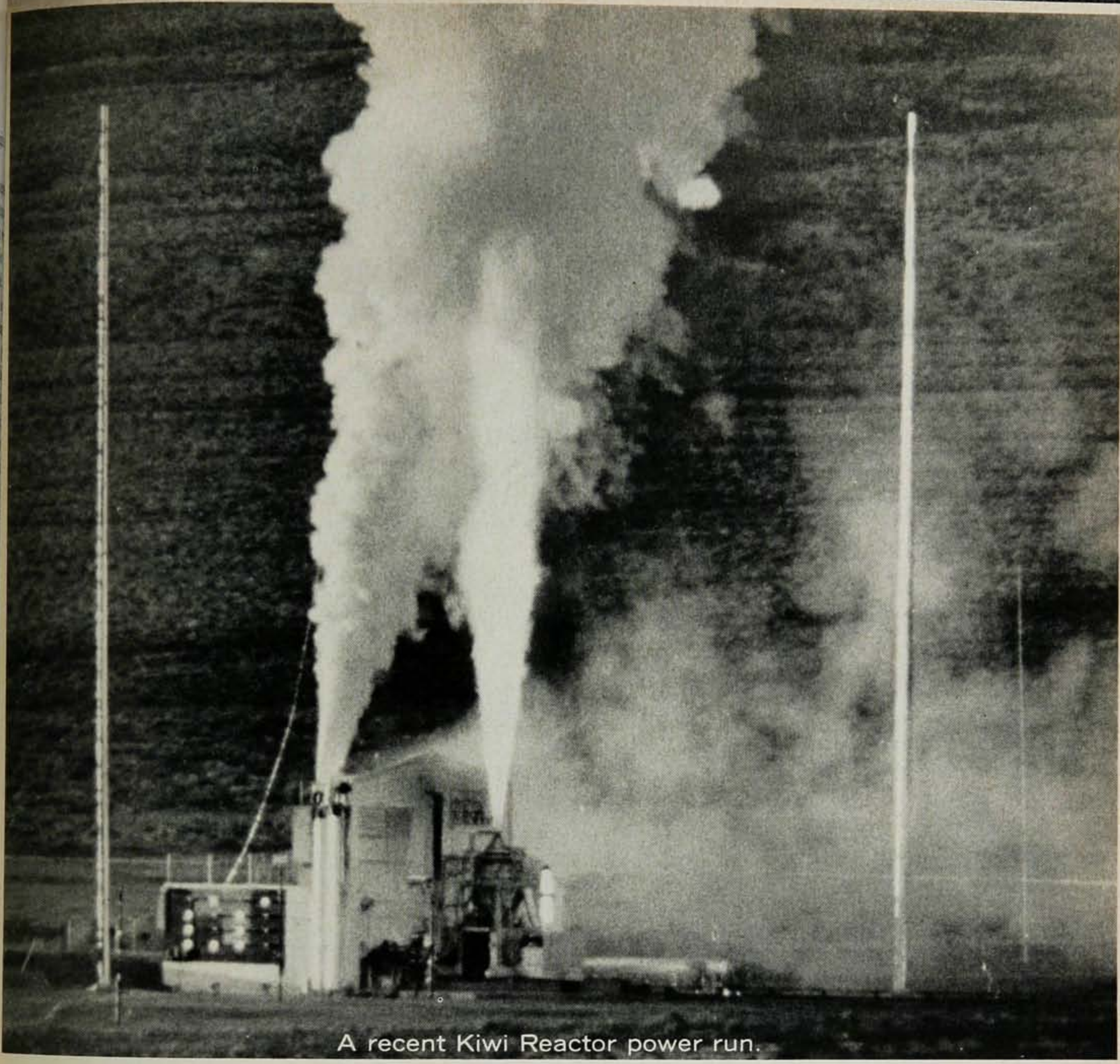
In contrast, Zijlstra reported noise levels in agreement with theory on specimens used for the space-charge limited-current measurements, which have a very small surface-to-volume ratio. This leads van Vliet to suggest a surface skin effect on cadmium sulfide, in which conductivity modulation of the surface layer accounts for the large noise level in standard-shaped specimens. This view is partially confirmed by preliminary measurements on a 400-ohm indium diffused layer on a cadmium-sulfide crystal, in which conductivity fluctuations similar to those seen in regular crystals can be measured. It is presumed that carrier interchange between the bulk and the surface skin modulate the conductivity of the surface layer. This model can also account for Epstein's observed reduction in transverse noise upon application of a Hall magnetic field, in that the field changes the symmetry of carrier diffusion, which may reduce carrier interchange between the bulk and surface. Clearly, an experimental study of surface-to-volume ratio effects in cadmium sulfide should be carried out to confirm this picture.

However, van Vliet also described a simple model in which giant fluctuations are calculated when the quasi-Fermi levels associated with occupancy of the conduction band and traps do not coincide. It is quite satisfying to have demonstrated that giant fluctuations can be expected in regular Markov processes when quasi-thermal equilibrium does not hold. In van Vliet's simple model, the giant fluctuations are associated with a superlinear photoconductive response region.

The g-r noise associated with acceptor levels in germanium-doped, high-resistivity, p-type In-Sb was described by W. Pagel. The $1/f$ noise in such specimens varies with the change in the surface potential produced in a field-effect experiment. Pagel finds that accumulation layers are much less noisy than inversion layers, which is similar to previous results for germanium. Infrared detectors made from such crystals appear to be photon-noise limited (300°K radiation) when operated at liquid-nitrogen temperatures.

The noise spectra from tellurium under 3.5-micron radiation can be resolved into three simple relaxation spectra. These results, together with the observed change from a linear to a square-root photoconductive response, are analyzed by V. A. Vis in terms of a two-trap model. Reasonable agreement is obtained between noise-time constants and the majority carrier lifetime from photoconductivity response. The dark noise in tellurium has a simple g-r spectrum at room temperature and becomes very much larger at liquid-helium temperatures.

E. Erlbach elaborated on recently reported measurements of the hot carrier temperature in germanium, using Nyquist noise. When the applied electric field is along the [110] crystallographic direction, the various conduction-band valleys should be heated unequally, and this is observed as a temperature anisotropy in the noise measurements. The noise temperature reaches 4000°K in the [100] direction and is approximately a



A recent Kiwi Reactor power run.

factor of four smaller in other orientations. At a lattice temperature of 77°K, the electron temperature is linear in an applied electric field although an initial-square-law behavior might be present. Above fields of the order of 1200 volts/cm, the electron temperature increases very rapidly. Erlbach feels that it will be possible to get a measure of intervalley scattering and energy-relaxation noises from noise-temperature data obtained in different crystallographic directions.

Impact ionization breakdown noise in germanium at 4°K is attributed by J. E. Hill to pulse-breakdown effects at the electrodes. The noise spectra show a f^{-4} trend at high frequencies and relaxation-time constants not explained by a *g-r* analysis. Hill interprets the results in terms of the time constant of the contact breakdown and the response-time constant of the plasma which is driven by the pulses. Above about 10^6 cps, *g-r* noise is observed and cross sections of 10^{-13} to 10^{-12} cm^2 are computed from the data.

Among the special topics discussed were preliminary measurements on fluctuations in the electroluminescent-light emission from MgO by T. M. Chen. The light noise is attributed to carrier fluctuations and has a time constant of about 10^{-5} sec. These first measurements indicate that the noise is many orders of magnitude greater than photon shot noise.

Examination of critical-point polarization fluctuations in ferroelectric triglycene sulfate at the Curie point has been carried out by J. J. Brophy by measuring the noise voltages between electrodes applied to the crystal. The results can be interpreted in terms of Nyquist noise of the sample conductance which attains very small values at the critical temperature. The low-frequency polarization fluctuations are very large and show a simple relaxation spectrum with a time constant of 5×10^{-3} sec. The results indicate that the time constant associated with loss mechanisms in TGS is relatively independent of temperature near the Curie point.

Resistance fluctuations in superconducting wires of vanadium, tantalum, and tin are used by B. Lalevic to investigate dynamics of the intermediate state in superconductors. This is possible because the interface domain energy dominates the free energy in the intermediate state. In vanadium, the observed resistance fluctuations are quite large and the velocity of domain propagation can be determined from the time constant of the noise pulses to be 60 cm/sec. The fluctuations are smaller in tantalum and still smaller in tin, in qualitative agreement with known domain sizes. A sample-size effect is noticed in that resistance fluctuation peaks are observed at the critical current when the sample size is of the order of the domain size.

An innovation in the conference this year was a round-table discussion of fluctuation problems. Space does not permit a full description of the subjects mentioned here. It is clear from the discussions, as well as from the results described at the meeting, that random phenomena are destined to play an ever-increasing role in the understanding of physical effects in solid materials.