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1/f noise in GaAs: Evidence of a new scale invariance

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Low-frequency noise measurements were made in the temperature range of 77–340 K on submicrometer resistors made from GaAs grown by molecular-beam epitaxy. Two types of noise were found, depending on surface treatment. One type consisted of discrete spectral components which showed no anomalous statistical behavior. The other type was a small $1/f$ component which showed anomalously large variations in spectral density, with these variations themselves having a $1/f$ spectrum.

For many years there have been two general approaches to the question of the origins of $1/f$ noise and other strongly nonexponential relaxation and fluctuation phenomena. One approach is to look for some reason for a set of parallel processes, which individually have exponential kinetics, to have the necessary distribution of characteristic rates.[1-3] The other approach is to look for a set of processes whose kinetics occur in a series, with the form of the linkage between the fast and slow processes determining the overall kinetic form.[4-7] Although these two approaches can each predict the principle forms of nonexponential kinetics if suitable assumptions are made, they lead to very different predictions for the behavior of systems small enough to allow measurements either of individual transitions[8,9] or of nontrivial statistical properties in the fluctuations other than the ordinary power spectrum.[10,11] In this paper we report evidence that $1/f$ noise in submicron GaAs resistors, unlike $1/f$ noise in several other systems,[10,11] shows statistical properties inconsistent with parallel kinetic models.

We observed two types of noise in our samples. One consisted of a set of discrete spectral components whose properties were entirely consistent with a model of a superposition of two-state processes, such as carrier trapping. When this noise was mostly removed by surface treatment, a small amount of $1/f$ noise with unusual statistical properties remained. (See Fig. 1.) Although the $1/f$ noise is our topic we will also briefly describe the discrete noise, described in much more detail elsewhere.[12]

The GaAs was grown by molecular-beam epitaxy on a chrome-doped GaAs substrate. On a typical sample, a 0.5-μm buffer layer of undoped GaAs was grown followed by an 0.15-μm layer of GaAs doped with Si at $n=7\times10^{17}$ cm^{-3}. Hall measurements were performed on samples from this wafer and yielded a mobility μ of 2780 ± 50 $cm^2/V\,sec$ and a carrier density n of $(7\pm0.4)\times10^{17}$ cm^{-3} at 300 K; and $\mu=2640\pm50$ $cm^2/V\,sec$, $n=(7\pm0.4)\times10^{17}$ cm^{-3} at 77 K. Noise sample GaAs No. 1 was prepared using a single chrome mask with an anisotropic etch [$8(H_2O_2):1(H_2SO_4)$]. The first few attempts resulted in invisibly cracked central regions, so the wafer was oriented to produce a central region having a wider base than top for structural stability.

In an attempt to make a smaller sample, a mask was made by scratching a randomly discontinuous line approximately 1 μm wide very lightly through the chrome of a chrome mask with a diamond scribe a number of times with different pressures, then using this as a mask with positive photoresist to generate another chrome mask (on unscratched glass with good optical properties) using a range of exposure times. This mask was used on GaAs wafers with a Shipley AZ 1450 positive photoresist, followed with the more isotropic etch [$1(H_2O_2):3(NH_4OH):15(H_2O)$] to etch a discontinuous "dotted-line" pattern. Another photoresist and etch process was then used to select one of the ~100 parallel resistors created by the dotted-line mask. Both processes resulted in samples with noise-generating regions having surface areas of ~1 μm^2 and containing $\sim10^5$ carriers.

Annealed tin contacts were used that resulted in Ohmic, quiet, problem-free, and mechanically strong electrical contacts. Details of the annealing procedure are described elsewhere.[12]

As discussed below, a commerical positive photoresist developer consisting of a NaOH solution (Micro-Posit 451 developer) was later used as a slow high-quality GaAs etch to reduce the thickness of the doped GaAs and clean the surface after the contacts were annealed to the sample.

Samples were mounted in an MMR Technologies tabletop refrigerator, with a computer-controlled temperature controller. Current for the noise measurements was supplied by a battery in series with a wire-wound resistor; voltages were amplified with a Princeton Applied Research 113 amplifier. Data were taken with an LSI11/23 microcomputer equipped with a SKYMNK array processor, an ADAC analog-to-digital converter, and computer-switchable antialias filters made by Frequency Devices. This system, as described previously,[10] allows the measurement not only of power spectra but of other statistical properties as well.

The power spectrum was computed from a series of 1024-point Fourier transforms. These were summed by

octave, and the means, variances, and covariances of these octave sums were calculated. Most typical noise sources are Gaussian, which implies that all higher moments, including these variances and covariances, are uniquely determined by the spectrum itself. (For example, all the covariances are zero for Gaussian noise.) When the variances were significantly above the Gaussian value, we recorded long series of octave sums and then took the power spectrum of that sequence of numbers to obtain a "second spectrum" which describes the time course of the variance in the noise.

The room-temperature spectrum was dominated by a single feature, somewhat broader than a Lorentzian. For more than ten octaves above the characteristic frequency, the spectrum fell off as $f^{-1.7\pm0.1}$. As the temperature was swept from 80 to 360 K, four such features, and what looked like the tail of a fifth, were found. Their characteristic frequencies could be fit by Arrhenius expressions. However, these frequencies also depended on the history of the sample surface (e.g., methanol cleaning, gasses allowed into the chamber at high temperatures, etc.), suggesting a dependence on surface potential. A crude gate capacitor was constructed from a 25-μm Mylar sheet and glued to the surface of one sample with acetone-diluted Duco cement, so as to be able to vary the surface potential reproducibly. The short-time effect (over several minutes) of changing the gate voltage was to change the characteristic frequencies of the noise features, with the greatest sensitivity at low temperatures. Neither temperature nor gate voltage nor most surface treatments had any major effect on the size of the discrete components of the noise.

Under these conditions, the noise was Gaussian, except for one sample which, near 180 K, showed a non-Gaussian component whose frequency dependence and second spectrum looked just like what would be expected for a single two-state system (i.e., trap) whose characteristic frequency landed near a minimum in the spectrum.

From the absence of detectable non-Gaussian effects in the steep part of the spectra, together with the measured sensitivity to the gate voltage, we determined that for these surface treatments the mean-square fluctuations in average surface potential would have to be less than about $2\times10^{-2}\,(k_BT)^2$.

The relative insensitivity of the noise magnitude to such surface treatment suggests that the discrete noise comes from the bulk, as one might also guess given the relatively sharp characteristic frequency distribution. Very likely the noise originated at discrete bulk trap types, with depths that intersected the Fermi level (thus allowing significant fluctuations) due to surface band bending. The effect of changing surface potential would then be to change which traps have fluctuating occupancy, but not necessarily how many traps are involved. The dependence of the kinetics on surface potential then suggests that the characteristic trapping-detrapping rates depend on distance from the surface, as would be expected if surface states are an intermediate in the process.

The two smaller samples, GaAs No. 2 and No. 3, exhibited a completely different form of non-Gaussian noise after certain surface treatments performed at room temperature. When these samples were cleaned using the developer solution, rinsed with deionized water, then exposed to a vacuum of approximately 1 mTorr using a two-stage oil pump for several hours, the previously sharp noise peaks would shrink and broaden, with the magnitudes decreasing by about a factor of 50 (see Fig. 1). The noise would stabilize after a few hours in the vacuum and become quite reproducible. (The removal of the discrete noise is consistent with our model for it, since the bands do not have to bend far enough or with the right sign to pick up the discrete noise.)

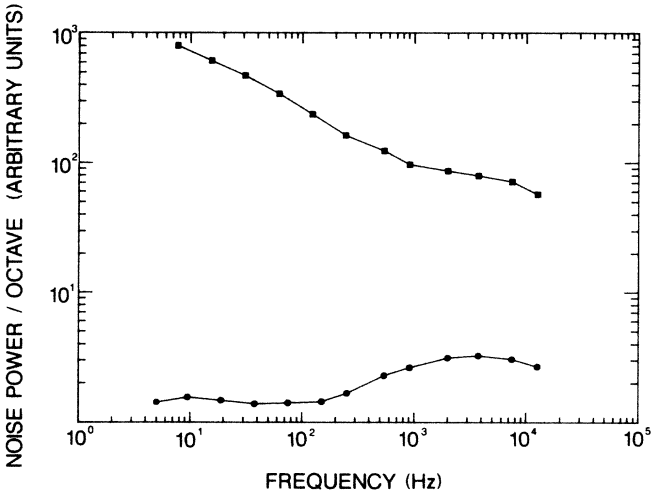

FIG. 1. The lower curve shows a typical octave-sum frequency spectrum for a GaAs sample (our No. 2) after NaOH etch and water rinse. The non-Gaussian fractional variance of the spectral density in this sample ranged from 0.06 in the lower frequencies to 0.05 in the higher frequencies. The upper curve is the spectrum, in the same units, on the same sample after methanol treatment. This noise was perceptibly non-Gaussian only in the upper decade, with a fractional variance of about 0.005.

The noise became very non-Gaussian with variances in noise power per octave as much as eight times the variance of Gaussian noise (see Table I). This extra variance was approximately proportional to the number of Fourier bins/octave as expected when much of the extra variance

TABLE I. This table shows a covariance matrix taken on the $1/f$ noise in GaAs sample No. 2 in the frequency range of 170 Hz to 19.5 kHz. The data are taken from 6000 Fourier transforms. On-diagonal terms give the ratio of the noise power variance to the Gaussian prediction. The off-diagonal terms are the correlation coefficients, not for the overall variance, but only for the extra non-Gaussian variance.

Octave	1	2	3	4	5	6	6.5
1	1.53	0.76	0.53	0.42	0.32	0.23	0.19
2		1.63	0.83	0.64	0.48	0.36	0.32
3			1.87	0.87	0.70	0.56	0.48
4				2.60	0.92	0.76	0.65
5					4.06	0.93	0.84
6						6.05	0.97
6.5							4.40

comes from noise power fluctuations on a much slower time scale than the inverse of the noise frequency.[10] The extra variance in noise power was usually almost independent of the frequency for the same number of bins/octave. In one case however, an increase in the variance at high frequencies corresponded to a decrease in the noise power occurring at the same frequency, and both the feature in the variance and the feature in the power spectrum itself had the same temperature dependence.

In all cases, the noise was still non-Gaussian after reexposure to air. To investigate the sensitivity of these non-Gaussian effects to surface conditions, sample No. 3 was then treated by painting a film of Duco cement diluted in acetone over the noise-generating region. This did not have a large effect on the non-Gaussian effects. Cleaning the sample with methanol increased the noise magnitude, especially at lower frequencies (see Fig. 1). This larger noise magnitude was much closer to Gaussian, but the higher frequency bands still exhibited the slow power modulations. All these results are consistent with the presence of a highly non-Gaussian approximately $1/f$ component, together with remnants of the Gaussian discrete components.

Second spectra were taken on this non-Gaussian noise after several different surface treatments which preserved the large non-Gaussian effects. The second spectra show that the low-frequency power modulation responsible for the increased variance of the noise power has a power spectrum approximately $1/f$ itself (see Fig. 2), with a small white component about 0.1 as large as the Gaussian variance.

The white component is more easily measured in lower frequency parts of the first spectrum than those shown in Fig. 2, for reasons having to do with the system processing speed. Actual values varied from 0.0 to 0.2 of the Gaussian value. Such a component, with variations of roughly that magnitude, is expected for noise arising from a superposition of random two-state systems.[11] We can estimate the density of such systems (which have a distribution both of characteristic frequencies for their Lorentzian spectra and of duty cycles) contributing to the noise at any time to be about 0.4 per (factor of e in characteristic frequency × factor of e in ratio of on to off times). The noise magnitude is consistent with such a density of electron traps, and would not be consistent with that density of two-state systems for transitions having much less effect on the conductivity than electron trapping.

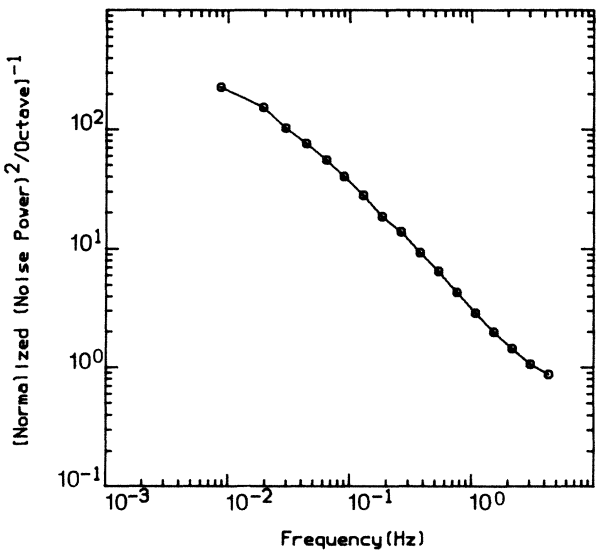

FIG. 2. Second spectrum taken on the noise in an octave band centered at 10 kHz in GaAs sample No. 2. The Gaussian prediction of 1.0 has been subtracted. The $1/f$ form of the spectrum was stable in time, and did not depend on which sample was looked at nor on which octave of the ordinary spectrum was chosen for analysis.

The large $1/f$ modulation of the noise power is not consistent with a simple superposition of two-state systems. This intriguing result could arise from a number of sources, including fluctuations in some single degree of freedom affecting the noise at all frequencies in the same way, such as amplifier gain or effective sample size, which depends on surface potential. We checked this possibility by looking at the off-diagonal terms of the covariance matrix, the correlation coefficients for the noise in different octave bands.

The correlation coefficients $r(i,j)$ for the power fluctuations in the ith and jth octaves are well defined regardless of the detailed statistical properties of the noise. When, however, each octave shows variance well in excess of the Gaussian value we can compute another useful correlation parameter

$$r'(i,j)=r(i,j)[\psi(i)\psi(j)]^{1/2}/\{[\psi(i)-1][\psi(j)-1]\}^{1/2},$$

where $\psi(i)$ is the variance for octave i, normalized so that Gaussian noise gives 1. The r' values are, roughly, the correlation coefficients for the excess variance whose origin is being sought. Table I shows the covariance matrix for sample No. 3 with the off-diagonal terms being the $r'(i,j)$ and the diagonal terms being $\psi(i)$. The small values of $r'(i,j)$ for nonadjacent octaves show that the excess noise variance in the different octaves is not completely correlated. We checked the calibration of the system by measuring a similar matrix on an otherwise Gaussian noise source for which the amplifier gain was twiddled; the resulting values of r' ranged from 0.94 to 0.99.

Thus the extra variance is definitely not due to some overall drift in sample properties which has a similar effect on different fluctuating sites. The $1/f$ spectrum of this extra variance would not result from drift (which gives $1/f^2$) anyway.

Another possibility would be that the spectrum consisted of superposed Lorentzians from carrier traps, but with some amplitude modulation of each trap's noise as the Fermi level in its vicinity drifted up and down, for unspecified reasons. Such a model would give a well-defined prediction for how the $r'(i,j)$ fall off for $i \neq j$. The results in Table I are very close to that prediction, as shown in Fig. 3. It is extremely unlikely for several reasons that the Fermi-level changes could be due to overall samples drifts. The large magnitude of the non-Gaussian effects would require fluctuations in the Fermi level more about two orders of magnitude larger than could have been present for the samples which showed mainly discrete noise components.

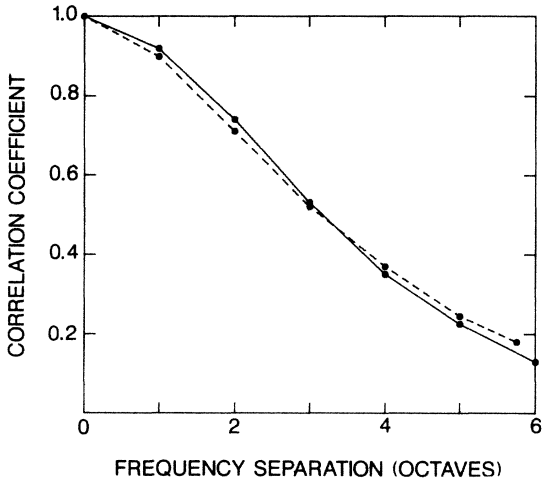

FIG. 3. The solid line connects points for the predicted correlation coefficient of the non-Gaussian variance of the noise in different octaves computed on the assumption that the noise arises from Lorentzians with a $1/f$ distribution of characteristic rates, each of which has an independently modulated amplitude. The dashed line is taken from the average of off-diagonal terms in Table I. Similar data were consistently found on the other sample, after several months sitting in ambient atmosphere, and in other frequency ranges. There are no adjustable parameters in this plot.

Furthermore, we would be unable to explain why the samples with larger remnants of the discrete components show smaller non-Gaussian effects precisely in those regions of the spectrum known to be affected by the average surface potential. The reproducibility of the magnitude of the effects in similarly treated samples would not fit well with such an explanation.

The relative magnitudes of the $1/f$ and white portions of the second spectrum provide further information. If we assume that the white part of the excess second spectrum is of about the same size as is obtained for a static ensemble of two-state systems with random times and duty cycles, and that the $1/f$ part results from a modulation of the intensity from each site, we find that the mean-square fractional modulation is of order unity. Thus it appears that each site is somehow turned off and unable to fluctuate for half or more of the time. The noise source is not even approximately a superposition of static, independent two-state systems.

If some form of series kinetics were involved, however, the $1/f$ second spectrum and the covariance matrix might make sense. If the ability of some fluctuating element to contribute to the noise in a given frequency range could be turned on or off by neighboring elements, as in some kinetic Ising models,[6,7] it would show noise power fluctuations with characteristic times typical of neighboring slower elements. The effect of neighboring elements with faster times would only be to renormalize the bare time of a single site. Thus the similarity of the second spectrum to the spectrum itself would not be fortuitous.

However, the close agreement between the interoctave correlation coefficients and the prediction for independently modulated Lorentzians indicates that the bare times of the separate sites are themselves distributed, as in other $1/f$ systems.[11] That agreement would be very hard to obtain if each site had a range of characteristic times induced by the intersite coupling. It is highly suggestive that in small metal-insulator-metal junctions, trapping transitions which are mutually exclusive are occasionally directly observed.[13]

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