

Effects of vacuum conditions on low frequency noise in silicon field emission devices

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(Received 25 August 1996; accepted 4 November 1996)

The effects of pressure on emission current noise have been studied. Field emission currents from 50×50 arrays and single emitter silicon devices were observed over a range of pressures. The current fluctuations were analyzed in both the time and frequency domain. Signal to noise ratios between 0.9 and 6.9 were observed and appear to be more dependent on operation time and current than on pressures. At higher pressures, emission currents are reduced and the current is cut off completely above a threshold pressure which is somewhere in the 10 s of Torr. Plasmas were observed in the mTorr range. The total current from a 50×50 tip array was measured to be only one order of magnitude greater than that for a single tip, suggesting that only 4–10 of the emitters in the array were functional. Spectral density coefficients of low frequency measurements range from 1.37 to 1.81. Some pressure dependence is suggested in the lower pressure ranges. The single emitter exhibited burst noise with a cutoff frequency of about 10 Hz. © 1997 American Vacuum Society. [S0734-211X(97)01302-4]

I. INTRODUCTION

Vacuum microelectronic devices are quickly becoming established as a viable technology for flat panel displays and other electron gun device applications. Consequently, it is increasingly necessary to understand aspects of device noise and lifetime. Factors associated with device lifetime include tip destruction due to ion bombardment, excessive emission current, and contamination of the emitter tips. One very important method of investigating these phenomena is through the study of the environment in which the emitters are operating, for instance, by attaching a residual gas analyzer to a system and studying the outgassing of phosphors or the emitters themselves.¹ Another method is to study the device noise under various conditions, for example, different system pressures, and to relate these data to specific events, i.e., noise. Furthermore, as device applications become more diverse, an understanding of the noise characteristics of individual tips is becoming important. Knowledge of such characteristics is vital to the design of any vacuum microelectronic device.

Device noise can most simply be observed by monitoring the changes in current over time. Such information may be used to quickly assess the stability of a device. By measuring the average current and observing the deviation from the average, it is possible to obtain signal to noise ratios, a key device design constraint.

Another method of observing noise is in the frequency domain. This method, though not as straightforward as simple current observations, may be used to give insights to the types of noise contributing to the total fluctuation. This information is valuable in determination and removal of noise sources.

There are two major types of noise that become apparent when these types of measurements are done. The first and

most noticeable is flicker, or $1/f$ noise. This type of noise is described by

$$S(f) = \frac{C}{f^\gamma}, \quad (1)$$

where $S(f)$ is the noise power, dependent on the bandwidth, γ is the spectral density index, and the value of C is dependent on the magnitude of the measured voltage or current. The $1/f$ behavior of this type of noise ranges from dc to some higher frequency where other noise sources become dominant. The spectral density may vary between 1 and 2 and has been measured between 1.1 and 1.8 for silicon field emitter devices.^{2,3}

The second type of noise that may be observed in the low frequency spectrum is burst noise. Burst noise also follows a $1/f$ type of response, however, since the bursts normally have a minimum frequency, there is a cutoff frequency at some finite frequency above dc. The spectral density for burst noise is normally near 2.^{4,5}

In this study we examined the low frequency emission current fluctuations from silicon field emission devices under different vacuum conditions. Initial measurements were performed using array devices evaluated under a vacuum of 2×10^{-6} Torr. These data are compared with data obtained from arrays and single emitters tested under better and worse vacuum conditions. In addition to $1/f$ noise, the extent of fluctuation was observed. Variation of current with time, independent of frequency, was measured and the signal to noise ratio determined. By considering all of the above observations, an impression of nature of the noise characteristic to these devices and the dependence of such noise on pressure is obtained.

II. EXPERIMENTAL PROCEDURE

Noise measurements were done using 50×50 emitter arrays and single emitter gold gated silicon field emission de-

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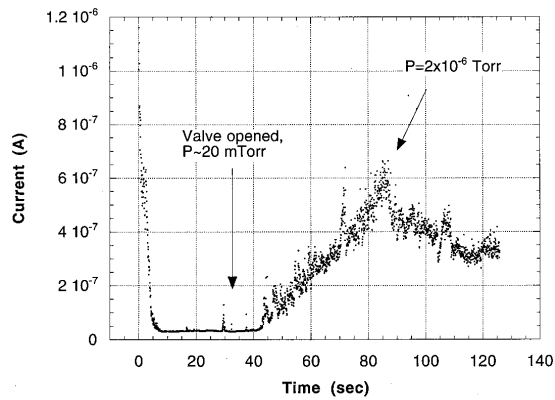


FIG. 1. The change of current with change in pressure.

vices fabricated using the method previously described.^{3,6} The gate and cathode were controlled using a semiconductor parameter analyzer which was able to source and monitor the terminals. The devices were tested under dc conditions at fixed gate voltages. Field emission electrons were collected using a metallic or phosphor anode located between 0.5 and 3 mm from the gate/cathode structure. Electrical contact to the anode was made via a feedthrough at the opposite end of the vacuum chamber from the gate and cathode leads. Anode biasing was done by directly connecting the parameter analyzer to the anode. This allowed measurement of the anode current at each sample interval. Since the minimum sample interval of the parameter analyzer was limited to 8 ms, the frequency spectrum was limited to below 62.5 Hz.

Measurements were done at pressures between 2×10^{-2} and $< 10^{-8}$ Torr. The measurements at $< 10^{-8}$ Torr were done in a separate chamber. The other measurements were done in the same chamber using the gate valve on the ion pump to control the pressure above the base pressure. Neither the devices nor the chambers were baked out prior to the study.

Current data were observed in three different ways. First, general trends of the current magnitude were observed on 50×50 arrays at different pressures. Next, current fluctuations over time were observed and the signal to noise ratio

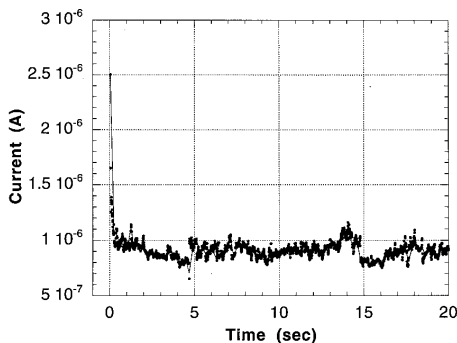


FIG. 2. Typical current-time data measured at 2×10^{-6} Torr. Note the initial high current.

TABLE I. Average current, signal to noise ratio, maximum and minimum currents from 50×50 arrays at different pressures. $V_{\text{gate}} = 24$ V.

Pressure (Torr)	Average I (μA)	S/N	Max I (μA)	Min I (μA)	Comment
2×10^{-4}	1.07	2.3968	4.36	0.816	
2×10^{-4}	0.96	2.1526	3.88	7.84	
2×10^{-4}	0.92	6.5097	1.19	6.17	After 30 s
2×10^{-5}	1.29	2.1311	5.65	1.00	
2×10^{-5}	1.27	2.1675	4.74	0.90	
2×10^{-5}	0.83	6.9703	1.11	0.68	After 30 s
2×10^{-6}	1.36	2.0893	4.86	0.86	
2×10^{-6}	1.22	2.5574	1.93	0.62	
2×10^{-6}	0.70	6.8561	1.00	0.61	After 30 s
$< 10^{-8}$	2.92	3.2678	4.40	1.88	
$< 10^{-8}$	3.31	4.0878	4.89	2.41	
$< 10^{-8}$	3.23	3.9800	5.11	2.35	

was calculated. Finally, these time based data were converted into frequency space and the low frequency noise power spectra were obtained.

III. RESULTS AND DISCUSSION

General observations of the effects of pressure were done on 50×50 arrays of tips. Currents measured from the devices ranged from about 0.5 to $4 \mu\text{A}$. Factors affecting the current included gate bias and the number of tips on the device that were emitting. Current-time measurements were made at several different pressures. During the measurements, two observations about the current behavior were made. First, as the pressure was raised into the mTorr range, there was a threshold where emission stops completely. In some cases plasmas were observed before this threshold was reached. Once the pressure was brought back down into the range of operation, the emission current resumed. This phenomenon was observed for both anode and gate currents, suggesting that a large portion of the field emission current is being collected by the gate. Figure 1 shows a plot of current vs time where the chamber pressure was initially set above the stable emission threshold by closing the high-vacuum valve. The pressure was then lowered after 30 s by opening the valve. As the pressure dropped the emission current rose; when the pressure stabilized, so did the emission current.

The second observation was that the emission current dropped when the devices were turned on by immediately

TABLE II. Average current, signal to noise ratio, maximum and minimum currents from a single emitter at different pressures. $V_{\text{gate}} = 30$ V.

Pressure (Torr)	Average I (μA)	S/N	Max I (μA)	Min I (μA)	Comment
2×10^{-5}	0.058	2.6461	0.106	0.040	After 30 s
2×10^{-5}	0.030	3.1897	0.056	0.020	After 30 s
2×10^{-6}	0.164	1.7832	0.329	0.057	
2×10^{-6}	0.090	3.7949	0.123	0.063	After 30 s
2×10^{-6}	0.093	3.6664	0.132	0.063	After 30 s
4×10^{-7}	0.088	1.5638	0.260	0.027	
4×10^{-7}	0.058	1.6989	0.135	0.040	
4×10^{-7}	0.118	5.3628	0.136	0.087	After 30 s

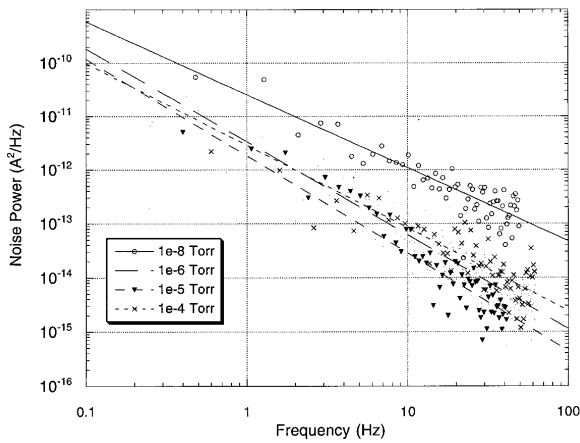


FIG. 3. Low frequency noise at various pressures.

switching the gate voltage to the bias value. The emission current initially started out at a high value, then dropped to a lower level in a few seconds. Figure 2 shows a current–time plot at a single pressure measured from when the device was turned on. Several measurements of anode current at fixed gate voltages were made at various pressures. In some cases the measurements were made when the device was turned on, in others the current was allowed to stabilize before noise measurements were taken. The average current, standard current deviation, and noise power–frequency response were calculated for each case. A signal to noise ratio was calculated by

$$S/N = \text{average current} / 2 * \text{standard deviation.} \quad (2)$$

The results of these measurements are tabulated in Table I for a 50×50 array device and in Table II for a single emitter.

In all cases the signal to noise ratio was never greater than 6.9. It was found that, if the emission was allowed to stabilize, the ratio became higher. In general, for arrays there was no significant difference in the S/N ratio at pressures between 2×10^{-6} and 2×10^{-4} . However, when the signal to noise ratio was highest, the current was at a minimum. At lower pressures, the values obtained were more consistent at higher current values. It is difficult to make any conclusion about the exact cause of the stabilization phenomenon. However, since the process was repeatable and was less noticeable in better vacuum, it may be that contaminant desorption is involved. The initial instability is consistent with observa-

TABLE III. Calculated spectral density at different pressures (50×50 array).

Pressure (Torr)	Spectral density
1×10^{-8}	1.3669
1×10^{-6}	1.7366
1×10^{-5}	1.8093
1×10^{-4}	1.5364

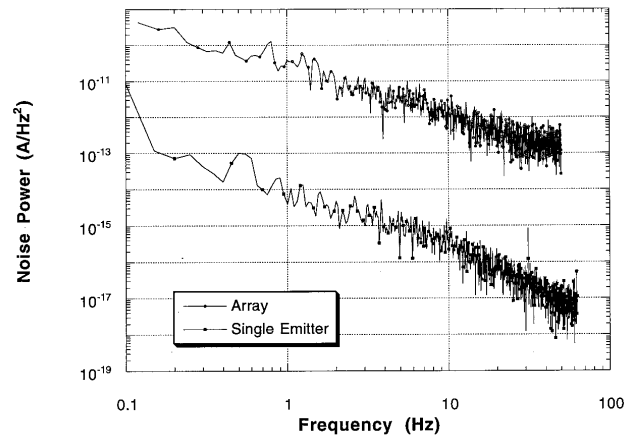


FIG. 4. Frequency vs noise power of a 50×50 array and a single emitter taken at 2×10^{-6} Torr. V_{gate} for the array is 24 V and V_{gate} for the single emitter is 30 V.

tions by Busta *et al.*⁷ Single emitter results are similar to those of the array, though the signal to noise ratio is smaller after stabilization.

An examination of the current levels observed from the two devices makes it possible to make some assumptions about the number of emitters that are functioning on the array device. It is expected that the amount of current extracted from a device is proportional to the number of emitters and the overall noise in an array is reduced by $n^{-0.5}$ where n is the number of emitters.⁸ Though the gate voltages of the data shown in Table I and Table II differ by 6 V, the difference between the average currents should be considerably more than just an order of magnitude if there are current contributions from a significant number of tips in the array. This is particularly true since current from the array was measured at as low as 20 V while the single emitter did not produce measurable emission until about 25 V, most likely due to physical differences in the emitters. Noting that the

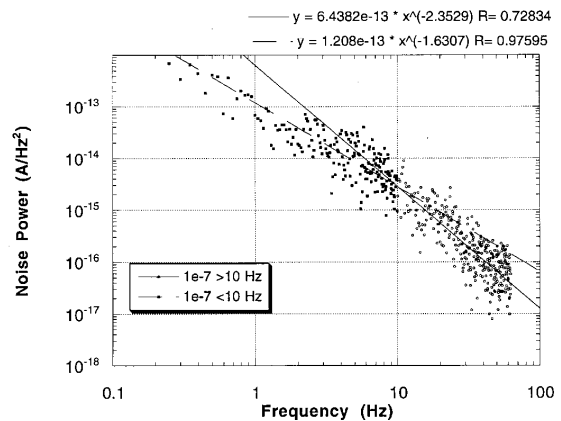


FIG. 5. Frequency vs noise power of a single emitter at 30 V. Curve fits are done to the portions above and below 10 Hz separately. The spectral density of the portion above 10 Hz is 2.3529. The discrete change in slope of the curve suggests the dominance of burst noise above 10 Hz.

TABLE IV. Calculated spectral density at different pressures (single tip).

Pressure (Torr)	Spectral density
1×10^{-7}	2.0307
1×10^{-6}	1.9926
1×10^{-5}	1.7966

average current from the array is on the order of $1 \mu\text{A}$ and that from the single emitter is about $0.1 \mu\text{A}$ and assuming that the emission scales with the number of emitters, it appears that only about 10 emitters are actually functioning. If the total noise should decrease by $n^{-0.5}$, the S/N should increase by

$$S/N_{\text{Array}} = \frac{S/N_{\text{SINGLE}}}{n^{-0.5}}. \quad (3)$$

When comparing the signal to noise ratio of the stabilized signals, at best the array S/N ratio is only a factor of 2 better which would indicate as little as only 4 tips are emitting.

IV. LOW FREQUENCY NOISE

Flicker noise was analyzed by converting current–time to noise power–frequency data using fast Fourier transform (FFT) calculations. Figure 3 shows the frequency space data of a 50×50 array at four different pressures. The straight lines represent curves fit to the noise equation (1), and the spectral densities from these fits are shown in Table III. The spectral density for the low pressure data is much lower than the others and there is a trend towards increasing γ until 2×10^{-4} is reached. At this point γ starts to lower once again. The reason for this is not known, however, since measurements were done at constant gate voltage rather than constant anode current, it may be that the change in γ may be related to a drop in emission current at higher pressures.

A single emitter was also analyzed. Similar measurements to the 50×50 array were taken. In this case the spectral density appeared to be much greater. Also, there was virtually no difference between the values at 2×10^{-6} and 2×10^{-7} , whereas in the 50×50 array the trend was for this to γ increase as the pressure raises. Figure 4 shows the frequency–noise power plot of the above array ($V_g = 24 \text{ V}$) and a single emitter ($V_g = 30 \text{ V}$) measured at a pressure of 2×10^{-6} Torr. Note that the noise spectrum of the array is linear when plotted on this scale, however the single emitter spectrum is not. There is a distinct bend in the spectrum of the single

emitter at about 10 Hz. When these data are separated near the bend (as is done in Fig. 5) it is possible to obtain a spectral density value for both portions of the curve. Doing this shows the spectral density for $f < 10 \text{ Hz}$ is 1.6307 and that for $f > 10 \text{ Hz}$ is 2.3529. This distinct cutoff suggests that, for the single emitter, burst noise is a dominating factor. In the case of an emitter array the burst noise is averaged and the flicker noise, common to all the emitters, becomes the dominating factor. Table IV lists the fit single-emitter spectral densities at several relevant pressures.

V. SUMMARY

Several observations of noise have been made on gold gated silicon field emission devices. These devices showed signal to noise ratio between 2.1 and 6.9 for the arrays and 1.5 and 5.4 for the single tip. Though the signal to noise ratio did not change with pressure, it did change with the total amount of current. The current level, however, was found to be influenced by the chamber pressure in two ways. The first was that the current was not present at pressures above a few mTorr, and increased as the pressure was lowered. Second, after a device was turned off for a few minutes, then turned back on again, the initial current was much greater than the final steady-state current. In this way the signal to noise ratio was influenced by pressure.

Low frequency flicker and burst noise was also observed. Both the arrays and single emitter exhibited flicker noise. In the case of the arrays a slight dependence on pressure was found by observing the spectral density. The single emitter spectrum was dominated by burst noise at frequencies greater than 10 Hz.

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