Modeling the Radiated Emissions from Microprocessors and other VLSI Devices

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Abstract

This paper presents a heuristic model for describing radiated emissions from microprocessors by considering the emissions spectrum to be that which would be produced by an electron gas. The main idea is derived from a modification of the classical Maxwell-Boltzmann distribution of molecular velocities in an ideal gas. In this paper, that procedure is applied to the free electrons in a conducting surface, where the electrons are assumed to be in a gas state residing over the surface of the conductor. Using the conductor volume, and the excitation signal characteristics, a distribution is found that roughly corresponds to measured distributions found in microprocessors.

Measurement Description

The initial motivation was the observation that blackbody radiation, and the Maxwell-Boltzmann distribution used to describe it, appeared to have a structural similarity with the measured spectral distribution seen in microprocessors. This observation followed a series of measurements performed using a variant of the standard TEM cell. The TEM cell used is described in Society of Automotive Engineers (SAE) specification 1752/3, Integrated Circuit Radiated Emissions Measurement Procedure, and is manufactured by Fischer Custom Communications.

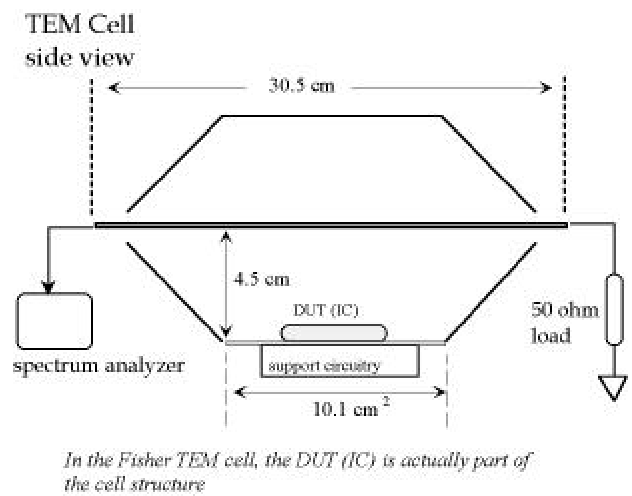


Figure 1 SAE IC TEM cell

The following plot shows the measured spectrum for a discrete digital core. The digital core consisted of: 16 bit microprocessor operating at 16 MHz, flash memory and ASIC (Application Specific Integrated Circuit).

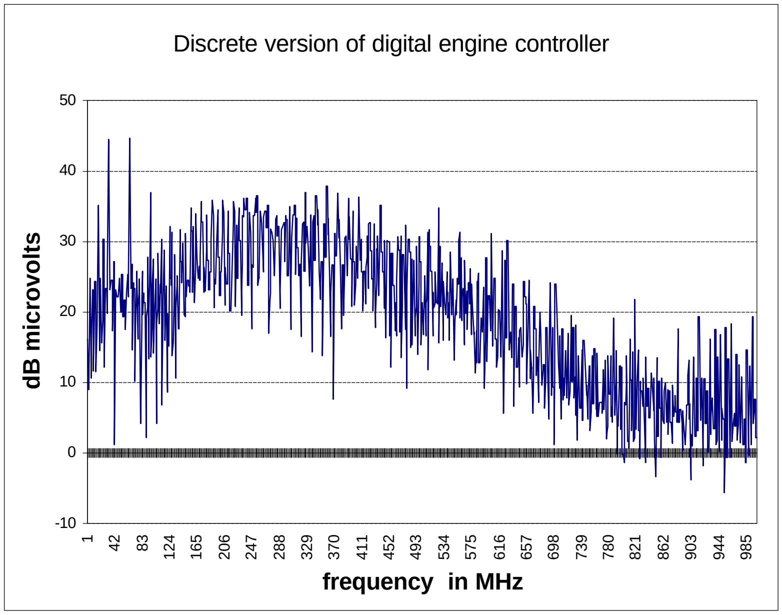


Figure 2

Modified Maxwell-Boltzmann Distribution

The Maxwell-Boltzmann energy distribution is a description of the motion of molecules in a gas.

Equation 1 is the standard result showing the Maxwell distribution in molecular speeds. Figure 3 shows a graph of the equation.

$$g(v)dv = \frac{4}{\sqrt{p}}\left(\frac{M}{2kT}\right)^{\frac{3}{2}} v^2 e^{-\left(\frac{Mu^2}{2kT}\right)} dv \qquad \text{Equation 1}$$

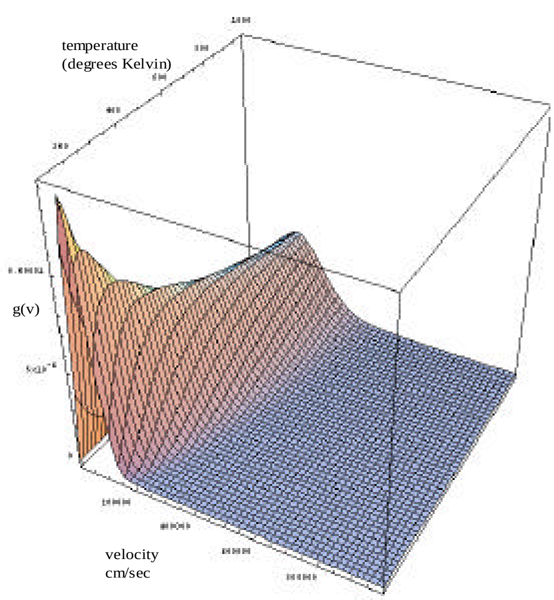


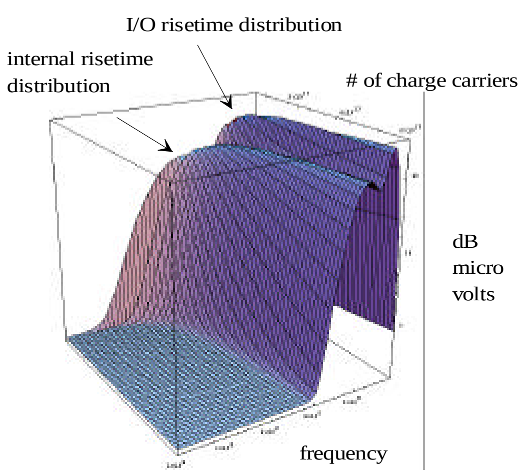
Figure 3
Molecular gas with varying velocity and temperature

It was noted that the distribution in speeds as a function of frequency appeared to be similar to the distribution of radiated emissions amplitudes as a function of frequency of the microprocessors measured with the Fischer TEM cell. This led to attempts to modify the Maxwell-Boltzmann equation that would describe the distribution of amplitudes as a function of frequency. By approaching the description of the radiated emissions from VLSI (Very Large Scale Integration) devices in this manner, the actual interconnect structure could be removed from consideration; instead of considering an array of radiating dipoles, the problem is approached from the viewpoint of radiating charges alone. The modified Maxwell-Boltzmann distribution of emission levels as a function of frequency is given in equation 2

$$D(f) = K\sqrt{\frac{16}{\pi}}\left(\frac{v^2 \frac{t_r h}{c^2} f \sqrt{\frac{N_e e^2}{t_r \, m \varepsilon_0 c}}}{2\pi \, \varepsilon}\right)^{\frac{3}{2}} f^2 \, \mathrm{e}^{-\left(\frac{v^2 \frac{t_r h}{c^2} f^3 \sqrt{\frac{N_e e^2}{t_r \, m \varepsilon_0 c}}}{2\pi \, \varepsilon}\right)} \quad \text{Equation 2}$$

In equation 2, the electron velocity from equation 1 has been replaced with the frequency of emission; $\frac{M}{kT}$ by $\frac{v^2 \frac{t_r h}{c^2} f \sqrt{\frac{N_e e^2}{t_r \, m \, \varepsilon_0 c}}}{2\pi \, \varepsilon}$, where N_e is the number of electrons driven by a particular rise-time; *v* is the average velocity of the electrons in the gas, and is determined by the type of material, the voltage applied, and the temperature; t_r is the rise-time; h is Planck's constant; e is the fundamental electronic charge; *m* is the electron mass; *K* is a function of the number of charge carriers and the conductance of the material and is approximately equal to 50000 .

The following graphs show calculated emission amplitude distributions as a function of frequency when one of the following parameters is varied: number of charge carriers; charge velocity.



velocity=const=1000 M/s

Figure 4
Varying the number of charge carriers

As Figure 4 shows, increasing the number of radiating charges increases the level of the emissions amplitude but moves the center of the spectrum downward and compresses the bandwidth.

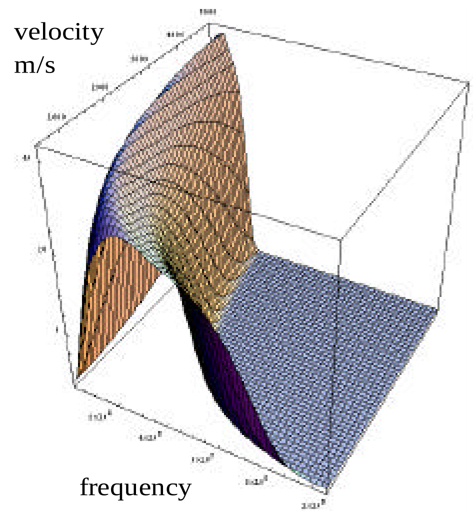


Figure 5
Varying the velocity of the charge carriers

Figure 5 indicates that slower charges will radiate at higher frequencies, but have an overall lower emissions level.

If the temperature is increased we expect the drift velocity to decrease, and vice versa. Figure 5 showed the effect of varying the velocity, where we saw that a decrease in velocity brought the emission amplitude down but moved it higher in frequency, while increasing the velocity brought the amplitude up and the spread in frequency down. This is in keeping with the fact that increasing the temperature increases the resistance, hence lowering the drift velocity, while decreasing the temperature increases the drift velocity. Additionally, Equation 5 shows a direct relationship between velocity and electric field. By increasing the electric field strength, the velocity increases. When the velocity increases, the emission amplitude increases and the center frequency moves down in frequency, while decreasing the velocity decreases the amplitude but moves the emission spectrum upward in frequency and spreads it out. We know, at the PCB level, that placing a signal trace as close to the ground plane as possible reduces the emissions levels, at the same time increasing the electric field between trace and ground. But, even though the electric field is increasing, it is becoming more directed in z axis, normal to velocity, thereby reducing the velocity component in the direction of the charge velocity and therefore decreasing the emissions levels.

The following series of comparisons of analytical and measured take the measured spectrum, with 1001 measured points, and compares against the predicted. The measured spectrum has been smoothed with a 16 point moving average for a clearer presentation and comparison.

Comparing the Modified Maxwell-Boltzmann with Measurement

The following graph, Figure 6, shows a comparison of the calculated amplitudes (using Equation 2) versus the actual measured amplitudes for a 16 bit microprocessor. The measurement was made at ambient temperature.The following assumptions were made when using Equation 2:

Discrete circuit implementation

velocity = 675 m/s

number of charge carriers = $1\ 10^{16}$
K_1 = 81000
K_2 = 36000

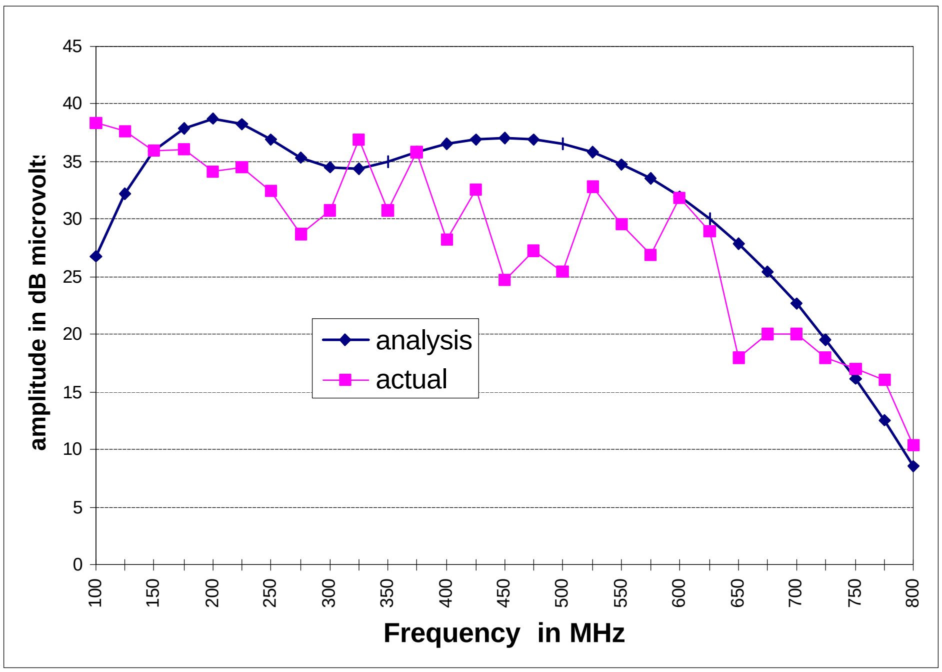


Figure 6

Given the modified Maxwell-Boltzmann distribution, is there an experiment that can be performed to indicate whether the model is reasonably predictive? One simple experiment is to vary the temperature that the circuit is operating in. This was performed with a discrete engine controller core, mounted on a mini-TEM circuit board and placed in the Fischer TEM cell. The cell was then placed in a variable temperature oven and the device was measured at ambient, 25° C; at -40° C; at 100° C. The following plot, figure 7, shows the results. The following assumptions were made when using Equation 2:

Hot measurement (Figure 7)
velocity = 200 m/s
number of charge carriers = $1.2\ 10^{17}$
K_1 = 26000
K_2 = 26000

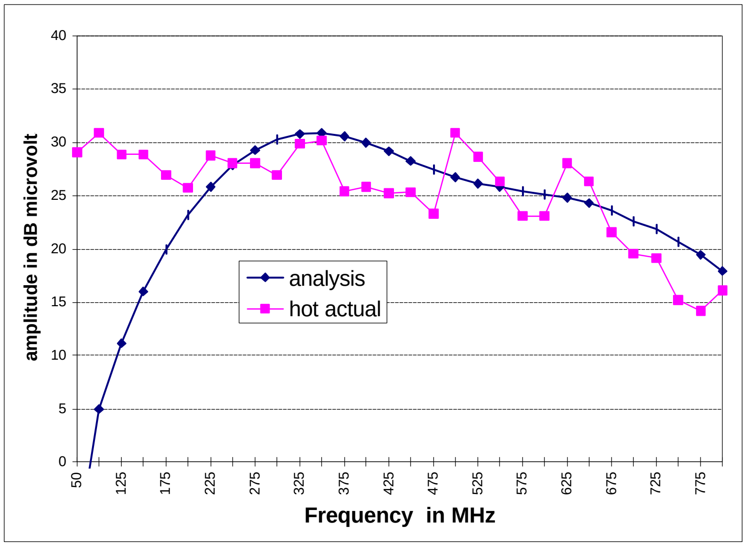


Figure 7

Cold measurement (Figure 8)

velocity = 850 m/s

number of charge carriers = $1.5\ 10^{16}$

$K_1 = 41000$
$K_2 = 18000$

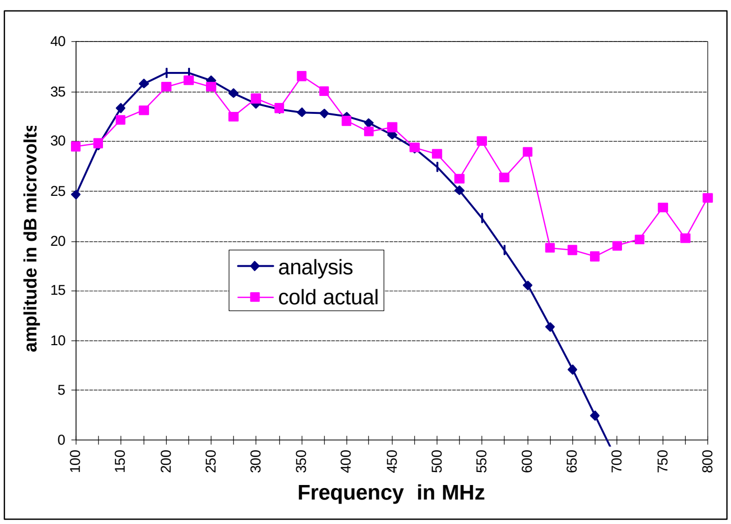


Figure 8

Equation 2, the modified Maxwell-Boltzmann, suggests that increasing the velocity should increase the amplitude of emissions and lower the distribution in frequency, while slowing the velocity will reduce the amplitude and shift the emissions higher in frequency. This is entirely consistent with the fact that switching speeds (velocity) will decrease as the temperature increases; which seems somewhat counter intuitive, but the hotter the gas, the more collisions occur, which directly affects the mean path length and therefore the velocity.

Figure 9 shows a smoothed comparison of the three measured temperature states.

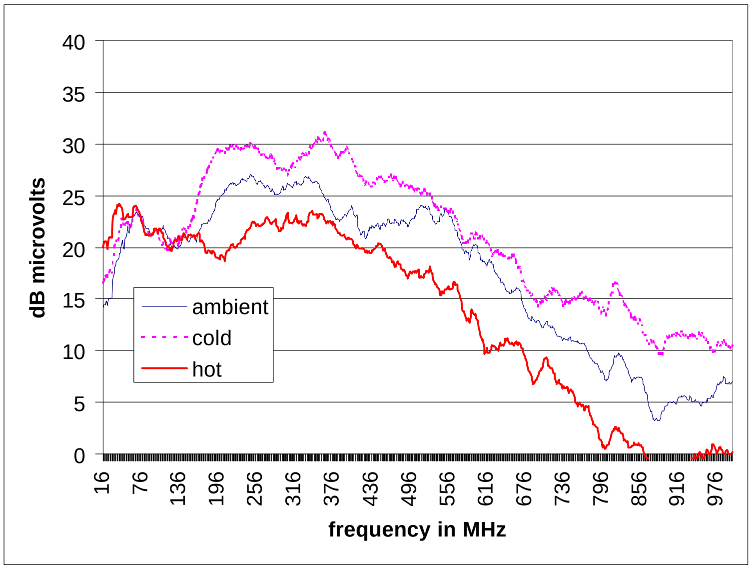


Figure 9

Comparison of the results from Equation 2 with the heat experiment shows reasonable agreement. The equation for the distribution of emissions as a function of frequency has two parameters: the number of charge carriers and the drift velocity.
In the hot model, the drift velocity will be lower than at ambient and more charge carriers are involved. For the cold model, drift velocity will be higher, and there will be fewer charge carriers.

Conclusion

The authors believe that the described model has heuristic value in explaining radiated emissions from VLSI devices, and also in PCBs with extended power and ground planes. A gas composed of conduction electrons is excited by the microprocessor (or similar source) and thereby radiates due to acceleration of the electrons. Does this approach allow a more intuitive picture of the actual radiative processes? Our answer would be yes, because it is easier to analyze the behavior of a gas than it is to analyze the radiation patterns of tens of thousands of interconnecting traces.

References:

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