Chaos, Solitons & Fractals 70 (2015) 38–41

Contents lists available at ScienceDirect

Chaos, Solitons & Fractals

Nonlinear Science, and Nonequilibrium and Complex Phenomena

journal homepage: www.elsevier.com/locate/chaos

A fractal approach to the dark silicon problem: A comparison of 3D computer architectures – Standard slices versus fractal Menger sponge geometry

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ARTICLE INFO

Article history:
Received 13 May 2014
Accepted 4 November 2014
Available online 22 November 2014

ABSTRACT

The dark silicon problem, which limits the power-growth of future computer generations, is interpreted as a heat energy transport problem when increasing the energy emitting surface area within a given volume. A comparison of two 3D-configuration models, namely a standard slicing and a fractal surface generation within the Menger sponge geometry is presented. In the following it is shown, that for iteration orders $n > 3$ the fractal model shows increasingly better thermal behavior. As a consequence cooling problems may be minimized by using a fractal architecture.

Therefore the Menger sponge geometry is a good example for fractal architectures applicable not only in computer science, but also e.g. in chemistry when building chemical reactors, optimizing catalytic processes or in sensor construction technology building highly effective sensors for toxic gases or water analysis.

1. Introduction

According to Moore's law [1] the size of computer chips and the price per transistor is decreasing exponentially for more than 40 years now. But in the future this development will come to an end due to the problem of heat production on multi-core chips. Despite the fact, that many attempts have been made to reduce heat effects in chips, e.g. reducing the power consumption, the design of state of the art chips comes to its limits.

Nowadays, a single chip produces energy densities comparable with nuclear power plants which turns out to be the major obstacle in upscaling multicore CPUs [2] and server-farms respectively [3]. The phrase "dark silicon" drastically describes the consequences for actual multi-core CPUs: large areas on a chip may only be used for a limited time and have to be switched off for a cooling period of time, which is steadily increasing with chip size.

One option, to overcome these difficulties, is the design of alternative chip architectures [4]. A promising direction is to make a step from 2D to 3D design [5]. In three dimensional space the control of heat generation within a given volume becomes an even more important task, which until now is an open problem in 3D-chip design and a field of actual research [6].

Let us state the problem with the following words: In 3D-chip design we have to find structures, which on one hand guarantee a maximum surface within a given volume, which means maximum computing power per volume and on the other hand a minimum of volume consumption, such that a cooling medium may occupy a maximal portion of the given volume, which results in maximum heat transfer and cooling.

To solve this problem, we suggest to consider a fractal approach, which is motivated by the observation, that similar problems have already been solved by evolutionary processes in nature.

http://dx.doi.org/10.1016/j.chaos.2014.11.004
0960-0779/

One example is the epithelial tissue, the material lungs are made of, which combines the requirements of optimum gas diffusion with minimum volume consumption and reveals a fractal structure under the microscope [7].

To model such a fractal structure, in the next section we will consider the properties of the Menger sponge [8], which may be considered as the 3D-extension of the 2-dimensional Sierpinski carpet [9], which itself already serves as a blue print for 2D architectures in technical systems, like building high quality antennas for mobile phones [10].

It is known [8], that the given volume of the fractal Menger sponge tends to zero, while the available surface tends to infinity while increasing the iteration number to infinity. In this paper we will compare another quantity: The available void volume, which gives space for cooling medium per unit surface for two different 3D-architectures.

It will be demonstrated, that there exists a threshold iteration number $n = 3$, above which a Menger sponge like architecture shows increasingly better thermal characteristics compared to a standard multi-core sliced ingot.

2. The models

We will consider two different models and investigate their thermal behavior when increasing the active surface area within a given unit cube V with size 1. Its dimensions may be measured in [m^3] to describe a server farm, in [cm^3] to describe multi-processor CPUs or in [mm^3] to describe a 3D-storage unit.

We consider the thermal active areas to be equivalent to the surfaces S_{model} on a passive 3D-substrate, which generates the volume V_{model} of the presented model.

The first model configuration is a simple sliced ingot:

Introducing an iteration variable n, which is correlated with an increasing number of slices of height L

$$L = \frac{1}{3^n} \tag{1}$$

and volume $1 \times 1 \times L$, we divide the unit-cube into ρ different slices,

$$\rho = \text{floor}(3^n/2) + 1 \tag{2}$$

which are evenly spaced within the cube and distance L apart from each other, such that a cooling medium, that fills the empty space, may be used for heat transport with a given velocity v. The volume V_s occupied by the slices follows as

$$V_s(n) = \rho L \tag{3}$$

and the corresponding surface S_s follows as

$$S_s(n) = \rho(2 + 4L) \tag{4}$$

In the left column of Fig. 1 the resulting configurations for increasing n are shown.

The second model configuration is the fractal Menger sponge. For a given iteration value n, the volume V_M is given by [11]

$$V_M(n) = \left(\frac{20}{27}\right)^n \tag{5}$$

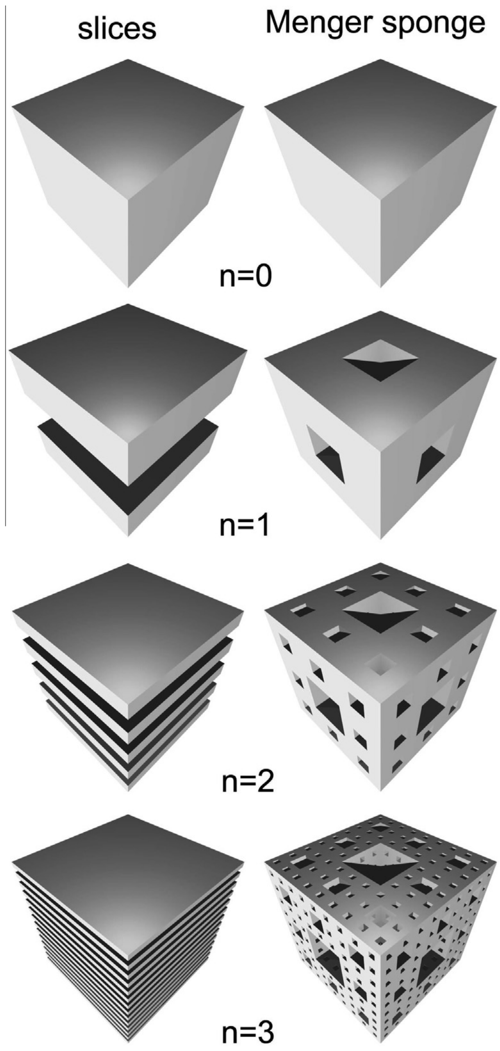

Fig. 1. A sequence of 3D-configurations for increasing iteration value n is shown. Every pair on the left illustrates the standard slice configuration, on the right illustrates the corresponding fractal Menger sponge model.

and the corresponding surface S_M is [11]

$$S_M(n) = \left(\frac{1}{9}\right)\left(\frac{20}{9}\right)^{n-1}\left(40 + 80\left(\frac{2}{5}\right)^n\right) \tag{6}$$

In the right column of Fig. 1 the resulting configurations for increasing n are shown.

In order to compare the thermal properties of each configuration, we insert the objects into a wrapping cube of size V_{tot}

$$V_{\text{tot}}(n) = (1 + 2L)^3 \tag{7}$$

which is considered as the container for a cooling medium, which covers a volume V_c

$$V_c(n) = V_{\text{tot}} - V_{\text{model}} \tag{8}$$

A measure of the efficiency E_{model} of a given configuration is the ratio of available cooling volume per unit surface