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Applications of Non-Linear Dynamics in the Production of Functionalised and Sensing Material

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Abstract. Certain applications of functionalised and sensing material require network of connectors such as conducting nano-wires, to pick displaced electrons or signals from an external source. Making nano-scale networks of connections that are durable, efficient and continuous is always a challenge for the material scientists. A possibility to achieve the above goals by mimicking dendritic and other diffusion patterns in nature is discussed here. These 'naturally grown' textures have the following characteristics that are very useful, as their intrinsic properties: 1. two branches will never overlap (saving material and avoiding any short circuiting), 2. all the branches will always have in contact with the root. Further, when it is practically impossible to develop a network of branches in an already existing solid material, induced dendritic growth using controlled diffusion can be used to do the job.

Introduction

In the pursuit for superior and complex electronic devices, better sensors, novel products and technologies, functionalised and sensing materials play an unmatched role. Current trends in nano-technology promise a whole different world of miniaturised or even molecular-level electronics that have aroused an unprecedented interest.

Micro- and nano-scale structures and material are essential component in functionalised and sensing material. A large number of researcher all over the world is currently engaged in producing nano-composites, nano-wires, nano-tubes, nano-clusters nano-particles and other nano material.

In nano-composite material as well as other applications involving thin films, oriented growth of nano-particles are commonly used. Traditionally, these nanoscopic components are fabricated on the surface of a substrate as large assemblies. Commonly, this is achieved by pre-structuring the substrate with a regular pattern of surface steps or bunches of steps.

Although self-assembling techniques have been used for over a decade for the development of nano-structures (e.g. [1-3]), only a few researchers made attempts to employ non-linear dynamics and its applications to the same. For e.g. Adelung et al. [4] reported the formation of nano-wires as small as 8nm in diameter, on a perfectly flat surface of layered transition-metal dichalcogenide (TMDS) crystals. They claimed to have net work of these wires extending to macroscopic distances. Interestingly they also reported the formation of variety of other nano-components such as triangles or parallelograms, nano-tubes & meshwork. As the substrate is perfectly flat with no step edges or other defects, these structures are formed by self-organisation of nano-particles.

In this paper an attempt is made to introduce some of the non-linear techniques that could be applied to produce functionalised and sensing material. The principles discussed here are scale-invariant and may be applicable to produce material regardless of the scale. Examples for such possibilities that already exist in nature are presented and discussed here.

Since this paper focuses on the potential of utilizing the non-linear dynamics, it has not been conventionally sectioned, such as methodology, results and discussion. Rather, selected models are discussed with some examples from nature and the potential applications. Detailed mathematical proofs are not presented here, as they can be found on the references.

Dendritic Growth and Diffusion Limited Models

One of the most explored self-organised patterns is the *dendritic* growth. After Witten and Sander [5] first described the theory, dendritic growths have been studied extensively using mathematical models and computer simulations [6-9]. These dendritic patterns are created mainly using diffusion limited aggregate (DLA) model.

Theory: The volume $V_{(l)}$ of an arbitrary object can be measured by covering it with particles of linear size l, and volume l^{dE}. Therefore $V_{(l)} = N_{(l)}\, l^{dE}$. $N_{(l)}$ is the number of particles to cover the volume. Since the volume of an object does not change with the unit of measurement, $N_{(l)} \sim l^{dE}$. When l^{dE} is not an integer, it is called fractal dimension d_f.

In general, diffusion limited aggregate (DLA) pattern can be denoted by the following non-linear equation:

d_f = Log N/Log (1/r) where is the size of a single step and N is the number of steps.

For DLA patterns, this value has been found to be around 1.7±0.1 [8].

In DLA model, particles diffusing in random manner (Brownian motion) are considered. Assume a system with particles have a higher affinity to its own kind than to the substrate or media. Whenever a randomly moving particle contacts another one, it stops and sticks to the other. This should lead to clusters, or “islands” randomly distributed in space.

However, if the initial particles are attached to a fixed point, the pattern will form around the point. For example, consider a negative electrode in an electrolyte containing metallic ions in small concentration. Any randomly moving ion will be deposited whenever it hits the electrode or the already deposited metal on it. Fig .1 shows a A radial pattern created using computer simulations. Similar patterns can be grown by diffusing material (particles) from a point source and are referred as DLA patterns. Each new particle added to the system will move to a “free edge” where it makes a contact with another particle, but not overlapping it. Similar pattern can also be created by releasing a particle from a circle. The particle will move until it has contact with another particle. Once in contact with a particle of same sort, it will be attached to the other particle and settle there.

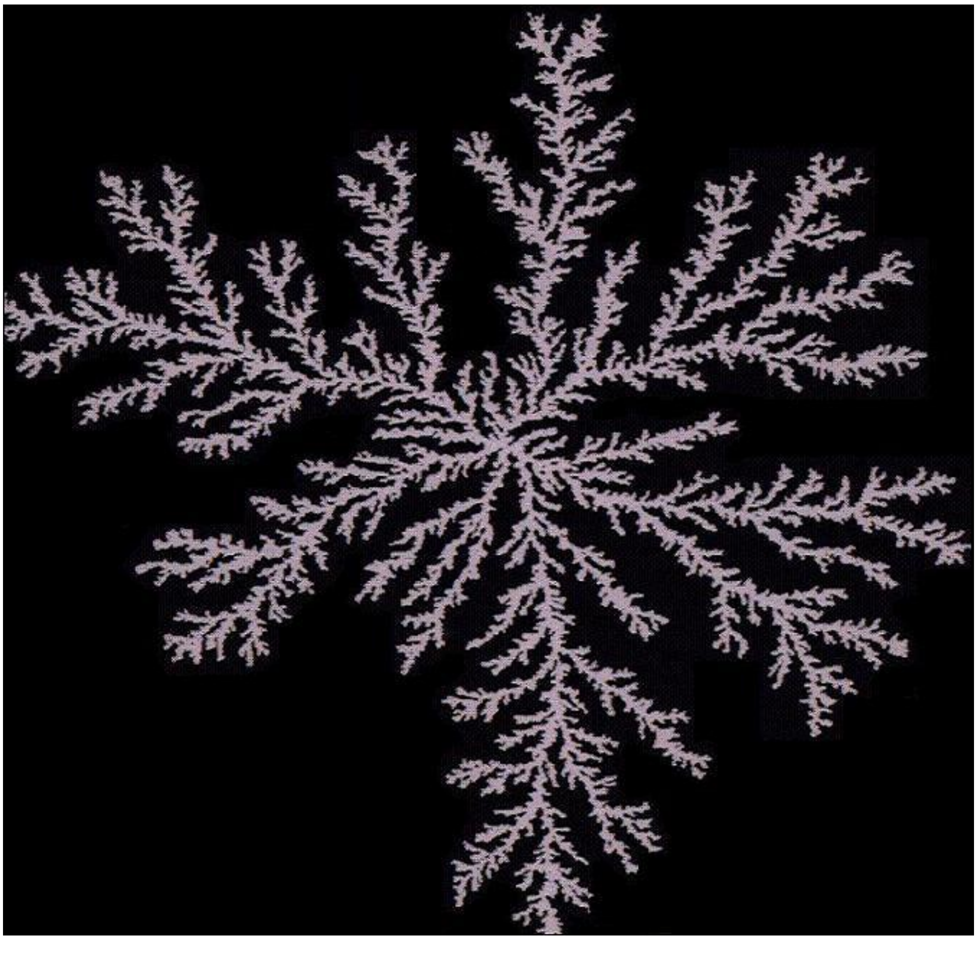

Fig.1 A computer simulated DLA pattern [9].

Naturally occurring DLA patterns have been discussed by many researchers [10-13]. DLA patterns are commonly observed in electro deposition (Fig. 2A), viscous fingering, mineral deposits (Fig. 2B) and thin films.

Fig. 2. A- Deposition of copper around a negative electrode from a copper sulphate solution [10]. B- Growth of manganese oxide (pyrolusite) on a sedimentary rock. Note the development of “fresh” branching into the open space while avoiding the contact with the self.

One of the striking characteristics of the dendritic patterns is the self-avoiding nature. Fig. 2B shows a dendritic pattern formed by mineral pyrolusite on a sedimentary rock. Close examination shows that the branches avoid each other and grow only into the open space.

Potential Uses. Dendritic growth of a conductive metal on a semi-conductive solar cell surface may collect the photo electrons more effectively. A structure like Lichtenberg figure has branchings that are thought to extend down to the molecular level [10]. One of the major advantages is the ability to “grow” large number of very fine branches which are definitely connected to the root. Moreover, there are no “short circuiting” or additional unnecessary links that would consume the branching material and add to the bulk. In contrast, micro- or nano-wires that were formed by pre-structuring the substrate make no guarantee that all the components would be interconnected in the most efficient way.

Another usage is when it is necessary to implant a connecting network over an already existing substrate, where traditional methods cannot be employed without damaging or altering the same. A dendritic growth may still be induced on the surface (2-D) or even through the 3-D space, as necessary. By controlling the diffusion rate, temperature, particle size and sticking probability, one can control the size, shape and extent of branching of the DLA pattern.

Other variations to DLA include Diffusion Limited Deposition, Diffusion Limited Cluster-Cluster Aggregation and Reaction Limited Cluster-Cluster Aggregation. Reader is referred to [14] for further details on those models.

Further, certain applications require nano-wires with varying composition along their length. There is a potential of producing such nano-wires by changing the composition of depositing material using the principle described here. It is suggested that by designing a manufacturing process to send the batches of different material at calculated time intervals, nano-wires with compositions varied along its length can be achieved.

Summary

Non-linear dynamics is well utilised for simulating the natural patterns. However, when it comes to the production of nano-wires and other functionalised material, its potential is still underutilised. Understanding the underlying principles will help produce better results and accelerate the development of nano-material, rather than experimenting blindly. Nature provides excellent leads for the scientists to follow. Some of the potential applications are discussed here using DLA pattern and its controlling parameters as examples.

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