Nano-Furnace Technology (NFT) with a nanostructured substrate or wafer

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Introduction

The nanostructured NFT non-conducting substrate for the CVD method and nanostructured NFT electron-conducting wafer for the liquid electrolysis method can solve the main problems encountered so far in the synthesis of carbon nanotubes (CNTs). With the standardized NFT process modules in self-sufficient and scalable NFT system containers at the energy sources, the climate-friendly, ecological, and economic use of previously unused energy such as flare gas [1] also becomes possible.

1. Carbon Nanotube synthesis

1.1 Carbon Nanotube

Among the carbon allotropes, CNT has become a center of attraction in the field of nanoscale research in modern science. Nanotubes are nearly one-dimensional structures due to their high length-to-diameter ratio [2]. Carbon nanotubes are the strongest and stiffest materials yet discovered in terms of tensile strength and elastic modulus. Because carbon nanotubes have a low density for a solid of 1.3 to 1.4 g/cm3, its specific strength of up to 48,000 kN·m·kg−1 is the best of known materials, compared to high-carbon steel's 154 kN·m·kg−1 [3].

1.2 Synthesis and scaling

Although many strategies have been opted for the synthesis of CNTs by CVD, efforts concerning the scale-up of CNT-producing processes still face contemporary challenges like slow growth rate (e.g., low nucleation efficiencies), poor yield (e.g., low carbon utilization and fast catalyst deactivation), and undesirable variations in material quality and lack of real-time process control. Nicole Grobert pointed out that Carbon nanotubes will only have a significant impact when they can be produced with uniform properties [4].

1.3 Chemical vapor deposition (CVD)

In general, the chemical vapor deposition (CVD) process [5] for nanotube fabrication can be divided into several steps. It generally starts with metal reduction, which leads to the activation of the catalyst nanoparticles. The catalyst particle promotes the decomposition of precursor molecules and the formation of a nanoscale carbon cap through the cross-linking of new carbon atoms and the formation of hexagonal and pentagonal rings. After the addition of the 6th pentagon, cap formation is completed, and the chirality of the future CNT is determined by the cap structure. From this point, the nanotube elongation phase begins by introducing new carbon atoms at the interface between the open end of the CNT and the catalyst nanoparticle, with the possible incorporation of defects. Growth termination can be caused by various reasons, such as catalyst encapsulation or catalyst ripening. This general description leaves open a large number of questions such as […] the chemical composition of the catalyst particle, localization of the catalyst, and tube-particle diameter ratio [6].

1.4 Liquid electrolysis method

In 2015, researchers at George Washington University discovered a new pathway to synthesize MWCNTs by electrolysis of molten carbonates. The mechanism is similar to CVD [7]. “An important component of the carbon-to-carbon nanotube growth process is transition metal nucleated growth of the CNTs. The nucleation occurs with metal migration from the anode as it establishes a stable oxide electrocatalytic anodic overlayer, or by the simple addition of metal oxides or metal powders to the electrolyte or cathode surface. In the absence of transition metal nucleating agents, CNTs are scarce, comprising < 1% of the carbon product. However, […] in the absence of transition metal nucleating agents […] other uniform products, Carbon Nano-Onions (CNOs), Carbon Nano-Platelets (CNPs), and graphene can be synthesized” [8].

1.5 Nanotube diameter

There are two configurations of nanotube growth: tangential and perpendicular. In the first case, the size of the catalyst particles is comparable to the nanotube diameter. However, in the second case, the size of the nanoparticle far exceeds the diameter of the CNT, which causes it to grow perpendicular to the catalyst surface, changing the interaction between carbon and metal orbitals during growth [9].

2. Methods for nanostructuring

2.1 Lapping surface technology

Lapping is a machining, possibly also manual, time-determined production process for smoothing surfaces (reduction of surface roughness) or for cutting off workpiece parts while maintaining close tolerances (see also DIN 8589 T15) [10].

Exemplary polishing services for metal substrates and metal wafers are provided by Valley Design Corp [11]. Shaped, diamond-lapped, abrasive-lapped, electropolished, buffed, fine polished, optically polished, or custom-processed metal wafers, metal substrates, and optics are available in most metals and in all sizes.

- Surface finishes: From rough machined to < 5 Angstroms
- Thickness: All thicknesses available to as thin as 10um
- Thickness Tolerance: Fractions of a micron are possible
- Geometries: From 300mm and larger to 1mm in diameter

- Different types of metal wafers and substrates processed: Aluminum, Copper, Nickel, Electroless Nickel, Brass, Molybdenum, Tungsten, Titanium, Stainless Steel 304, 316, 430, High Nickel Alloys, and Special Alloy Products.

2.2 Nanoimprint lithography

Nanoimprint lithography (NIL) is a non-classical method for high-resolution surface patterning. It has been shown in numerous publications that the pattern resolution in nanoimprint lithography is limited by mold fabrication rather than the printing process. Already in the early work of Chou et al. in the 1990s, the transfer of the smallest structure sizes down to 25 nm or 10 nm was shown. Later, it was reported that even the replication of dense lines with a width and spacing of 6 nm each and of single structures with a width of 2.4 nm is manageable. This possibility of high-resolution structuring in the range of single nanometers is one of the most important advantages of nanoimprint lithography [12].

2.3 Reactive ion etching

Both wet chemical (wet etching) and dry etching (dry etching) processes are used to transfer lithographically generated structures from a coating into underlying material layers. In the dry etching process, the removed materials are transferred directly from the solid surface into the gas phase, and more efficient transport mechanisms are exploited. The reactive components in the gas phase are accelerated directionally onto the solid surface. Therefore, the concentration of reactive constituents is usually much lower in dry etching than in wet etching [13].

2.4 Ion beam sputtering

Ion beam sputtering or ion beam deposition (IBD) is a process of applying materials to a target through the application of an ion beam. An ion beam deposition apparatus typically consists of an ion source, ion optics, and the deposition target. Optionally a mass analyzer can be incorporated [14].

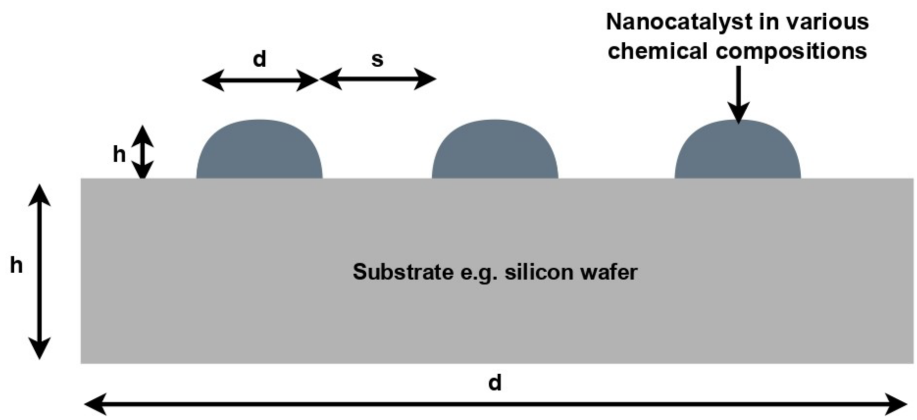
3. Nanostructured NFT substrate and wafer

Companies for the process of nanostructuring.

- Lapping technology: Stähli Läpp-Technik, Germany [15]
- Hardmaster: Nano Optics, Japan [16]
- Nanoimprint Lithography: EV Group, Austria [17]
- Ion Beam Etching, Ion Beam Sputtering: scia Systems, Germany [18]

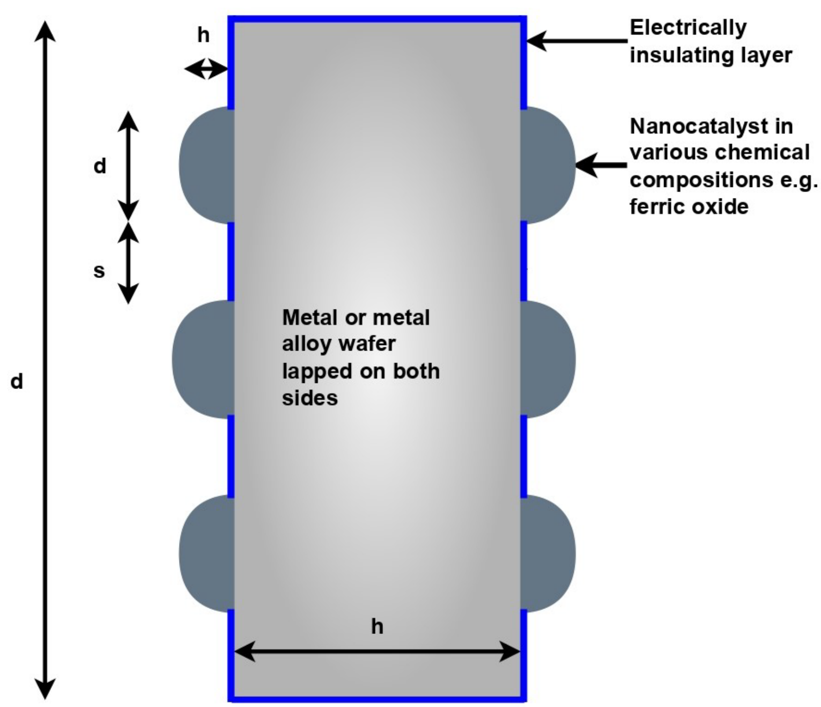
Nanostructured NFT non-conducting substrate

d diameter nanocatalyst e.g. 40 nanometers, h height nanocatalyst e.g. 20 nm, s space between nanocatalysts e.g. 40 nm; h height substrate e.g. 1 mm, d diameter substrate 300 mm and smaller.



Nanostructured NFT electron conducting wafer

d diameter nanocatalyst e.g. 40 nanometers, h height nanocatalyst e.g. 20 nm, s space between nanocatalysts e.g. 30 nm; h height wafer e.g. 1 mm, d diameter wafer 300 mm and smaller. The power supply line can be in the center or outside.



4. Continuous increase in value of carbon nanotubes and fibers

4.1 The major problems of CNT synthesis are solved

Via geometry and coatings with metals and metal alloys of different compositions, it is possible,

- to precisely and reproducibly control the diameter of the nanocatalysts and thus the diameter of the CNTs (for example, 40 nanometers),
- to set a precise and uniform distance between the nanocatalysts (for example 30 nanometers), which ensures unhindered growth,
- to prevent encapsulation and ripening of the nanocatalysts, which lead to inefficiency and stagnation.

4.2 Continuous increase of aspect ratio and tear length

The aim is a systematic experimental optimization of the process for ever longer synthesis times in batch operation with ever longer CNTs and ever larger aspect ratios, which is of great importance for the tensile strength of the fibers spun from them. Fiber strength and aspect ratio scale with nearly 1 (0.9), which is close to the expected linear dependence for stress transfer in shear for very long elements [19]. For diameter, the possibilities are limited by the limits of nanofabrication: 40 nm, perhaps 30, 20 nm in longer timescales. The potential is almost exclusively in longer CNTs: at 40 nm diameter and 40 µm length, the aspect ratio is 1000, at 400 it is 10,000, at 800 it is 20,000, and so on. CNTs with an aspect ratio of 4000 and more are spinnable, and fibers spun with CNTs with an aspect ratio of 4400 [20] have a tensile strength of about 2 gigapascals (GPA), which is equivalent to that of steel. Larger aspect ratios equate to greater tensile strengths and longer tear lengths with lower mass consumption of the products - and correspondingly higher values of CNTs and fibers.

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