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Heat-Induced Morphological Changes in Silver Nanowires

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Heat-induced morphological changes in silver nanowires

Abstract:

The main objective of this study was to investigate the degradation or splitting of silver nanowires when they go through varying temperatures, associated with processes such as frictional forces, Rayleigh instability, thermal expansion, and surface atom diffusion. To conduct this experimentation, a substrate of Nano-Tec ultra-flat silicon wafer was employed.

The samples were prepared by drop casting the solution of silver nanowires with the solvent ethanol. After this, they were allowed for the heat treatment.

The results from the investigation showed that silver nanowires undergo morphological alterations when exposed to heat, with the main variables of interest being different temperatures and durations of exposure. Initial experiments were done to analyze the changes in silver nanowires at different time intervals. The study also highlights the quantifying splits in adhered and suspended parts of the nanowires.

SEM (Scanning Electron Microscopy) was employed to capture magnified images of the silver nanowires, which aided in the measurement of diameters and lengths of splits for the compilation of statistical data. My role in this study was to measure and compile all the statistical data on heat-induced morphological changes that were observed on silver nanowires at alternating temperatures and durations.

Keywords: Silver nanowires, silicon substrate, scanning electron microscope, drop-casting, heat treatment, sintering, morphology change, fragmentation.

CERCS: P250 Condensed matter: structure, thermal and mechanical properties, crystallography, phase equilibria.

Kuumusest põhjustatud morfoloogilised muutused hõbeda nanotraatides

Abstraktne:

Selle uuringu esmane eesmärk oli uurida hõbedaste nanotraatide lagunemist või lõhenemist neid erinevatel temperatuuridel kuumutades. Muutused on tingitud nähtustest nagu pinnaaatomi difusioon, Rayleighi ebastabiilsus ja soojuspaisumine. Selle uurimise läbiviimiseks kasutati ülitasapinnalise Nano-Tec ränisubstraati, mille mõõtmed olid Ø6”/150mm <P/100> *ultraflat*. Katses kasutatud hõbedaste nanotraatide nimiläbimõõt oli 120 nm ja pikkus ulatus kümnete mikromeetriteni. Nanotraadid osteti ettevõttelt Blue Nano, Inc.

Hõbedast nanotraadid kanti räni substraadile lahusest tilgutades. Seejärel kuivatati substraat õhu käes ja kuumutati erinevate ajavahemike jooksul, et jälgida hõbedaste nanotraatide kuumuse poolt põhjustatud morfoloogilisi muutusi.

Katsetulemused näitasid, et hõbedast nanotraatidel esines pärast kuumutamistmorfoloogilisi muutusi. Kuumutades varieeriti temperatuuri ja kuumutamise kestvust.

Hõbedast nanotraatide piltide tegemiseks kasutati Skaneerivat elektronmikroskoopiat (SEM). SEM pilte kasutati nanotraatide morfoloogia kohtastatistiliste andmete kogumiseks. Minu peamine roll selles uuringus hõlmas hõbeda nanotraatide kuumutamist erinevatel temperatuuridel ja kestustel ja statistiliste andmete kogumist.

Märksõnad: hõbedast nanotraadid, ränisubstraat, skaneeriv elektronmikroskoop, tilgutamine, kuumtöötlus,morfoloogia muutused, fragmenteerimine.

CERCS: Tahke aine: struktuur, termilised ja mehaanilised omadused, kristallograafia, faaside tasakaalud.

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1. Introduction

The main goal of this study is to see how silver nanowires change morphologically when they are subjected to heat over different intervals of time. Subsequently, a detailed statistical analysis is conducted to quantify the diffusion of silver nanowires, focusing on both adhered and suspended sections. This analysis was constructed upon the no. of splits in silver nanowires across the series of experiments, which is done on silver nanowires deposited on a patterned silicon substrate [1]. When it comes to metal nanowires, especially silver nanowires in creating high-performance flexible transparent films, the one-dimensional nanostructures of these nanowires are of high importance. These films are of most importance for modern technology, such as smart windows and solar cells [2], touch screens [3], flexible sensors [4], temperature monitoring [5], medical materials [6], biocompatible polymer binders [7] and nanoscale system [8]. Heat-induced morphological alterations in silver nanowires can substantially affect the integrity of their structure, electrical conductivity, and overall functionality. Due to their versatility, silver nanowires have led to their application in various fields, such as transparent heaters, organic light-emitting diodes, touch displays, solar cells, and flexible electronics [9]. Transparent film heaters, in particular, have gained significant interest due to their combination of transparency and flexibility. These heaters find applications in wearable technology, display technologies, smart windows, and automobile defrosting systems [10]. As the size of the nanostructures decreases, their surface energy increases, leading to lower melting temperatures compared to their bulk counterparts. This phenomenon arises due to the increased surface area-to-volume ratio, causing a larger proportion of atoms to be located at the surface. As a result, the cohesive forces in between these nanostructures are very weak; hence they show low melting temperatures.

On the other hand, such size-dependent melting behavior has a very crucial impact on high-temperature applications and provides exciting opportunities to design materials with unique features of melting to benefit certain types of applications [11].

Moreover, when considering metal nanowires for use in such applications due to prolonged exposure to high temperatures the heat treatment of these seems also a key factor. Due to heat-enhanced surface atom diffusion, dramatic structural rearrangements of silver nanowires can easily be achieved provided the sample is heated to just below its melting point [12]. Moreover, this diffusion process may cause the elongation or bending of nanowires as well as even their merging to each other due to energetic interactions, thereby affecting the electrical, optical, mechanical properties.[13] Therefore, it is crucial to understand and control this behavior for the optimization of heat-treatment routes as well as to ensure the properties for silver nanowire-based materials [14]. Heat induced morphological modification of the silver nanowire is the focus for investigation in this study. The material and surface energy of the substrate affected greatly on structural change in silver nanowire during different heating processes. Heat treatment caused morphological changes are the primary facilitators of superior performance and durability in any silver nanowire application.

2. Literature Review

2.1 Metallic nanowires and their applications

Nanowires are one-dimensional nanostructures with high aspect ratios and diameters at the nanometer level [2],[15]. In particular, metallic nanowires are likely to be one of the fundamental parts of many industries and fields. Metallic nanowires are very sensitive to heat-treatment fragmentation, and which affects their functionality [1],[2]. Studies have demonstrated that the surface of gold nanowires can begin to melt at temperatures considerably lower than the bulk melting point [16].

2.2 Thermal Behavior of Metal Nanostructures under High Temperatures

Despite the well-known fact that at high temperatures metal nanostructures behave quite differently from their bulk counterparts, multiple studies have been conducted into how alternating heating conditions affect the thermal behavior of metal nanostructures, specifically silver. As the size and dimension of the nanostructures shrunk, the reduction in melting temperature becomes more evident. Nanoparticles usually exhibit reduced melting points compared to bulk [17]. There are many factors that could be the reason for reduction in the melting temperature observed in metal nanostructures. One noticeable element is the increased surface-to-volume ratio in nanostructures, which raises surface energy and weaker atom-to-atom bonds. The melting behavior of metal nanostructures can be attributed to the weakening of cohesive forces that keep them together, resulting in a lower melting temperature. For their functional uses, it is pivotal to understand how metal nanostructures act when they melt. It makes it possible to form and refine materials with specialized melting characteristics for specific uses. The melting course in nanoscale devices also offers potential for manipulating the melting and solidification procedures [18],[19],[20]. The alteration in surface energy due to size variation results in metal nanostructures exhibiting reduced melting points compared to their bulk counterparts. As nanostructures decrease in size, a higher proportion of atoms are situated at the surface due to the escalating surface area to volume ratio. The cohesive energy of the atom's converts because the atoms on the surface and the ones on the inside experience distinct bonding states. Metal nanostructures have gone through substantial research on the surface energy's fluctuation with size. The examinations have demonstrated that the enervating of atomic bonds at the surface, which happens due to the increased surface energy as compared to the bulk, is what causes nanostructures to melt at lower temperatures [21]

2.3 Heat-induced fragmentation in Nanowires:

Nanowires are highly sensitive to heat, and when exposed to thermal processes, they can fragment through mechanisms like Rayleigh instability [22]. This fragmentation occurs differently depending on the method of heat application [23], [24], [25]. Nanowires undergo rapid and intense heating upon exposure to a nanosecond-pulsed laser. irradiation, resulting in Rayleigh instability. This instability precipitates the fragmentation of the nanowires into smaller, more stable particles [26]. Conversely, when nanowires undergo thermal treatment in ambient air, the combined effects of heat and oxidation induce distinct morphological transformations [27],[28],[29]. Prolonged exposure to elevated temperatures in the presence of oxygen leads to the oxidation of the nanowire surfaces. This oxidation process, coupled with thermal energy, significantly alters the structural configuration of the nanowires [30], [31].

2.4 Morphological changes and surface atom diffusion

When nanowires are exposed to high temperatures, they experience a process called surface atom diffusion. In this process, an atom travels across the surface of nanowires because of the high thermal energy. As the temperature rises, these atoms gain enough energy to escape their regular positions, which then results in significant changes in the shape and structure of nanowires [32], [33].

2.4.1 Elongation:

Nanowires can stretch or elongate if the atoms on their surface start moving. This happens because atoms shift from areas with high curvature, which possess lesser stability, to areas with lower curvature. This movement makes the nanowires grow longer and thinner [1],[13],[34].

2.4.2 Bending:

Besides elongation, nanowires can also bend due to surface atom diffusion [35]. This bending happens when stress or thermal energy is not distributed evenly along the length of the nanowire, leading to an asymmetric atomic movement. As a result, the nanowire takes on a curved or bent shape [1], [36].

2.4.3 Merging

Atom diffusion is a process in which nanowires can often merge when placed close to each other. This occurs because the surface atoms of nearby nanowires move towards one another, effectively "welding" them together. This merging process can greatly impact the network of nanowires, affecting their overall properties [37].

2.5 Thermal Stability

The crystallographic surface and geometric structure play vital roles in the thermal stability of silver nanowires. This effect is clearly illustrated by comparing multiple types of silver nanomaterials including but not limited to, silver nanobelts and pentagonal silver nanowires. Silver nanobelts with low- energy (111) crystallographic surface presented excellent thermal stability. Due to the closely packed atomic structure, (111) surface is a low-energy surface and the corresponding crystallographic plane exhibits more stable morphology when subjected to thermal stress. This stability is important for applications which require higher thermal endurance, as the atoms in low-energy surfaces are less likely to migrate or diffuse, thereby maintaining the integrity of the nanobelt structure even at elevated temperatures.

In contrast, pentagonal silver nanowires contain high-energy (100) surfaces. The atomic structure on the (100) surface is more open compared with the (111) surface, thus resulting in a less stable surface. Therefore, pentagonal silver nanowires are easier to be thermally decomposed. As a result, the distinction in thermal stability arising from differences in crystallographic surface energies should be taken into account when designing and applying silver nanomaterials. For instance, silver nanobelts with (111) surfaces can be more suitable in some electronic and photonic devices demanding high thermal stability. In a similar manner, pentagonal monocrystalline silver nanowires which are less stable might be more appealing for some specific applications where the characteristic features of arsenic-metal NWs are needed but thermal stability is not critical. The inherent thermal stability of silver nanowires is largely dictated by the nature of their crystallographic surfaces. Silver nanobelts with low-energy (111) surfaces exhibit greater thermal stability, making them more resilient at high temperatures. In contrast, pentagonal silver nanowires with high-energy (100) surfaces degrade more rapidly under similar conditions. This understanding is essential for tailoring the use of silver nanomaterials in various high-performance applications [11].

2.6 Silver Nanowires as Transparent film heaters:

Silver nanowire networks have discovered a new use as an extremely bendable transparent film heater [10], [38] These heaters are appropriate for a variety of industries and applications because they combine transparency and flexibility [39]. Silver nanowire can be integrated into transparent or semi-transparent surfaces since they produce heat effectively while maintaining optical transparency [40]. Transparent film heaters can be designed and produced with more efficiency and sturdiness by taking advantage of the special qualities of Ag NWs, such as their superior electrical conductivity and mechanical flexibility [41]. Transparent film heaters built on Ag NW have benefits beyond flexibility and transparency. These heaters provide quick reaction times, even heating, and good thermal efficiency [39]. They can be employed in a variety of applications, such as wearable technology [42], display technologies [43], smart windows [44], and automobile defrosting systems [45]. The alignment and density of Ag NW networks have been optimized, as well as the adherence of NWs to substrates [12] and the use of advanced control systems for temperature regulation, to increase the stability and efficiency of these heaters [46].

3. Experimental Methods and Materials

3.1 Materials

3.1.1 Materials used in the preliminary experiments

Silver nanowires with a nominal diameter of 120 nm and lengths measured in tens of micrometers were acquired from Blue Nano, Inc. These nanowires are distinguished by their pentagonal cross-section and a unique five-fold twinned inner structure.

Silicon substrate used in this experiment was initially cut into 5 small pieces with the help of Laboratory Silicon Wafer cutting pen for R & D use KV SIC 150. Then the samples were placed onto a simple paper to avoid any dust particle adhesion with the silicon substrate. Silicon wafer used is Nano-Tec ultra-flat silicon wafer.

3.1.2 Materials used in Patterned Silicon substrate experiments:

In this set of experiments conducted by a colleague, the silicon substrate used was with patterns of rectangular holes which were prepared from (100) silicon wafers (Semiconductor wafer, Inc.) in four steps which are as follows:

1. Firstly, the conventional optical lithography used to produce the desired rectangular hole patterns in a photoresist on the wafer.
2. Secondly, the removal of silicon dioxide by using buffer hydro fluoride solution to replicate these holes on the oxide layer.
3. Then, silicon etching in tetramethylammonium hydroxide solution at 90 °C to form the etched holes followed by rinsing in hydro fluoride solution to remove the remaining silicon dioxide.

4. The results were that the formation of the patterned silicon substrate featured rectangular holes, with side lengths ranging from 3.6 µm to 5.3 µm and depths measuring several hundred nanometers.

The distance between the holes varied from several hundred nanometers to several micrometers, depending on the direction. The sidewalls of the holes had a slope of 54.7 degrees relative to the main surface of the silicon, corresponding to the angle between the (111) and (001) planes in silicon [1]

3.2 Sample Preparation and Heat Treatment

3.2.1 Preliminary experiment:

First, silver nanowires were diluted in ethanol to facilitate their separation from the meshwork. When silver nanowires agglomerate into a meshwork, their individual properties may be compromised, leading to reduced performance in applications where dispersed nanowires are required. Ethanol is used which is a common solvent with good dispersing properties, can interact with the surface of the nanowires and help break up the agglomerates, facilitating their separation and improving their dispersion in the solvent. Then, the solution is allowed to undergo sonication for about 10 minutes to achieve a homogeneous solution of the nanowires while preserving their integrity. Meanwhile, the hot plate was preheated to 150°C to ensure a consistent temperature distribution across its surface. Carefully dispensing a small volume of the prepared solution containing the silver nanowires onto the silicon substrate, relied on gravity for the even distribution of the nanowires. While gravity plays a role in the settling of nanowires during drop casting. It is not sufficient to ensure the even distribution of nanowires on a substrate due to the complex interplay of various factors such as solvent evaporation dynamics, surface interactions, capillary forces, and nanowire-nanowire interactions. Subsequently, the silicon substrate contained the droplet of solution of silver nanowires and ethanol was air dried for about 5 minutes to ensure firm attachment of the nanowires to the substrate. This procedure was repeated to prepare five more samples of similar kind. Then, all of these five samples were placed over the hot plate to facilitate the diffusion and disintegration of the silver nanowires. All five samples underwent heat treatment at 150°C for varying durations: 15 minutes, 30 minutes, 60 minutes, 120 minutes, and 240 minutes.

3.2.2 With Patterned Si-substrate:

An additional two samples in a similar manner were prepared by colleague like in the preliminary experiments using a patterned silicon substrate to study the effect of heat treatment on silver nanowires under two different heating modes. For this experiment, heat treatments were carried out in a muffle furnace (NABERTHERM, L-091H1RN-240)

In the direct heating mode, the samples were placed in the muffled furnace and heat was applied in 10-minute cycles at fixed temperatures, followed by cooling to room temperature. The first cycle was set at 100 °C. In each subsequent step, there was an increase in temperature by 50 °C until 200 °C, and then by 25 °C increments until 450 °C.

In the continuous heating mode, the muffled furnace was preheated to 375°C to 400 °C and then the sample was placed in the furnace for about 10 minutes [1]

3.3 Characterization

After subjecting the silver nanowires to heat, a Scanning Electron Microscope was utilized to analyze their morphological changes, surface features, and any modifications caused by the thermal treatment. The high-resolution imaging allowed for precise measurements of the nanowires, enabling statistical analysis of adhered and suspended segments as well as determining the average number of splits in the silver nanowires, providing a basis for repeated experiments investigating possible alterations in the nanowires.

4. Results and discussion

4.1 Preliminary Experiments

The main aim of this set of preliminary experiment was to investigate the impact of different heating durations on silver nanowires at a constant temperature of 150°C to induce morphological changes in the wires. In the 15 minutes sample, there was no evident change in the silver nanowires. It is clear in the comparison of Image 1 and Image 2 which is taken before and after heating the silver nanowires for 15 minutes at 150°C that the morphological change is negligible. There is a slight degradation of the silver nanowire noted at the bending site indicated as (a) in Figure 1, Image 2.

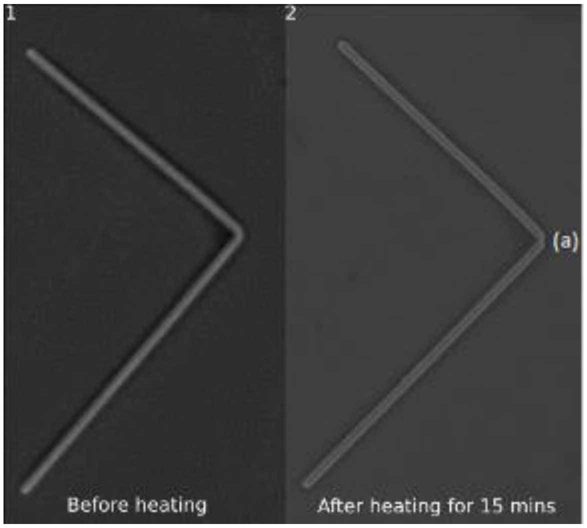

Figure 1. SEM Image 1 showing the nanowire before heating while Image 2 shows silver nanowire degradation at site (a) after heating for 15 mins at 150°C

The sample heated for 30 minutes at 150°C showed similar split behavior as in Image 2 of Figure 1. The bending sites are indicated as (a), (b), (c), (d) and (e) in SEM Image 2 of Figure 2. shows the splits of the same kind. The impact of heat induction on the morphological change in silver nanowire is the same if the nanowire is heated for 15 minutes or 30 minutes at 150C.

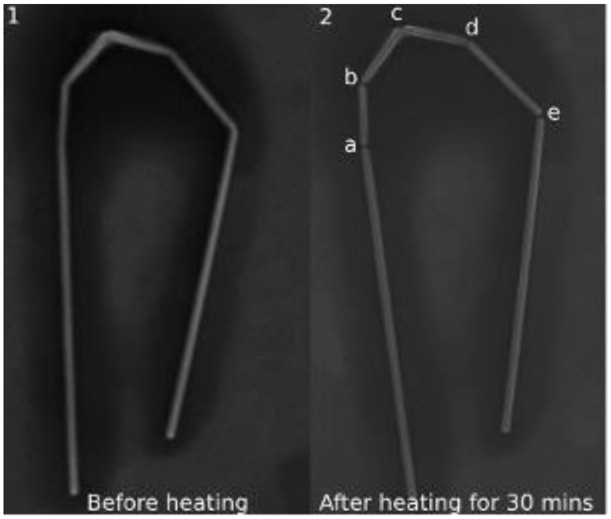

Figure 2. SEM Image 1 showing the nanowire before heating while Image 2 shows silver nanowire degradation at site (a), (b), (c), (d) and (e) after heating for 30 mins at 150°C

Stress and friction are crucial factors influencing the fragmentation process, especially in scenarios involving materials like silver nanowires. When subjected to heat treatment, these nanowires can undergo thermal expansion, leading to the generation of mechanical stresses which can be seen in SEM Image 2, Figure 3 at point (c) and (d). Thus, the sample which is heat treated for 60 minutes at 150°C showed relatively greater degradation at bending sites indicated as (a) and (b) while silver nanowires showed gaps due to diffusion as (c) and (d) in SEM Image 2, Figure 3.

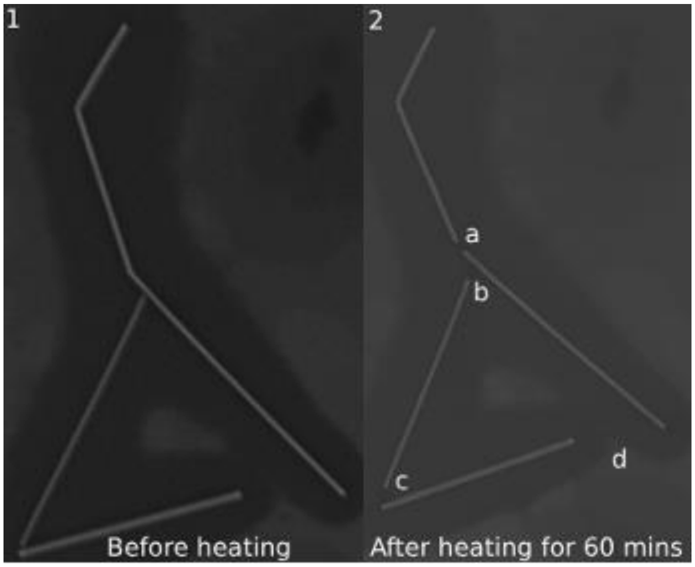

Figure 3 SEM Image 1 showing the nanowire before heating while Image 2 shows silver nanowire degradation at site (a), (b), and gaps due to diffusion indicated as (c) and (d) after heating for 60 mins at 150°C

Similar trend in the samples subjected to heat treatment for 120 minutes at 150°C was observed. They exhibited noticeable splits indicated as (a) but as such no prominent morphological change in silver nanowire can be observed which can be seen in SEM Image 2 in Figure 3 as below:

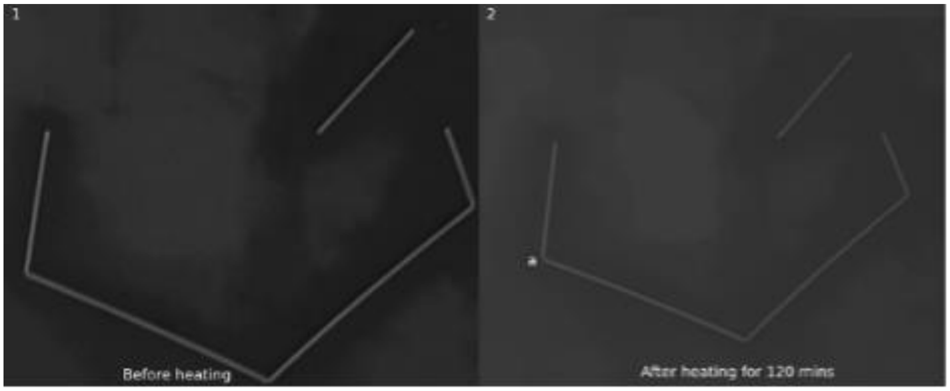

Figure 4. SEM Image 1 showing the nanowire before heating while Image 2 shows silver nanowire degradation at site (a) after heating for 120 mins at 150°C

The sample heated for 240 minutes at 150°C showed similar results which showed splits and gaps between the nanowires due to thermal stresses. Figure 5 showed SEM Images as 1 and 2 which are before and after heating. The splits as indicated as point (a), (b), (d) and (e) while point (c) showed that the nanowire not only degraded as split but nanowires protrudes or bulges similarly at point (f) and (g) which could be due to diffusion of silver nanowires at atomic level. While silver nanowire indicated as **x** in Image 1 before heating is seen as **x’** which is not even the half size of the original nanowire which is **x**. The reason could be that the thermal stresses caused the nanowire displacement or the degradation of nanowire due to less diameter as its comparatively thinner than the other.

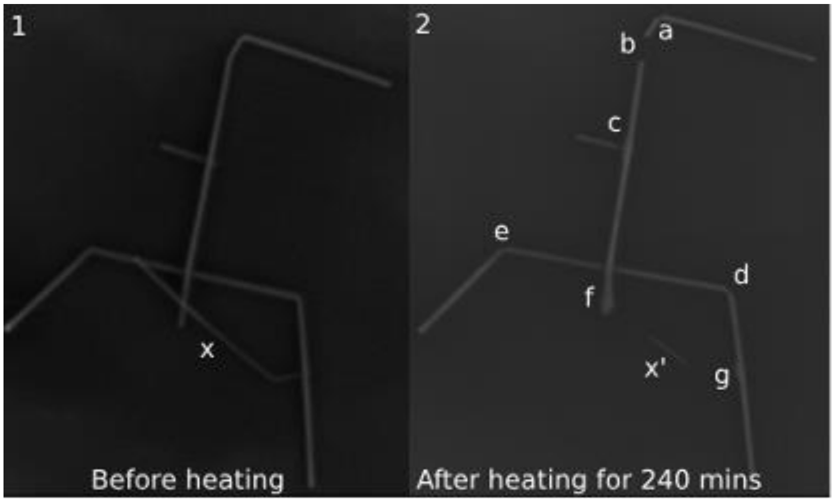

Figure 5. SEM Image 1 showing the nanowire before heating while Image 2 shows silver nanowire degradation at site (a) after heating for 120 mins at 150°C

In this set of preliminary experiments, the results indicated some morphological changes in the silver nanowires, but these changes were not as pronounced as anticipated. The time effect caused negligible morphological changes in silver nanowires in the form of splits and gaps between nanowires which could be due to thermal stresses or mechanical tension. Thus, to achieve more significant results a colleague worked on another set of experiments in which there was an increase in the temperature systematically by keeping the time constant for two modes of heat induction.

4.2 Experiments with Patterned Si-substrate

In this set of experiments the silicon substrate used is patterned silicon substrate which is why it is named as experiments with patterned silicon substrate. Sample preparation was similar to the preliminary experiments while silver nanowires were heated in a muffle furnace for two sets of heat induction named Direct mode and Continuous mode. Heating the sample in air as in hot plate method differs from the one in a muffled furnace because it isolates the material from external contaminants and allows for higher temperature treatments. Post heating, the Scanning Electron Microscope was used for the characterization of silver nanowires to observe and compare the morphological changes between the suspended and adhered parts.

In the direct mode of heat treatment, it can be observed that there is maximum number of splits in the adhered part indicated as **(a)** while the silver nanowires remain intact with the silicon substrate in the suspended parts indicated as (b) and (c) in Figure 6 for which the sample was heated at 400°C for 10 minutes.

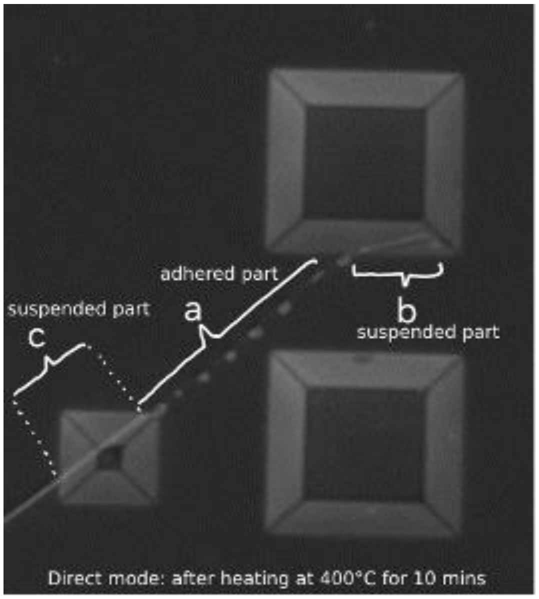

Figure 6. Direct mode: SEM image of Silver Nanowire over pattern silicon substrate heated until 400°C for 10 mins showing splits in silver nanowire in adhered part as (a) while intact at suspended part as (b) and (c)

In contrast, the continuous heating mode caused the silver nanowires to split at the suspended part indicated as (a) while the silver nanowire remained intact at the adhered parts indicated as (b) and (b’) in Figure 7. The sample was heated from 375°C to 400°C for 10 minutes. Overall, a decreased number of splits can be observed in continuous mode in comparison to the direct mode.

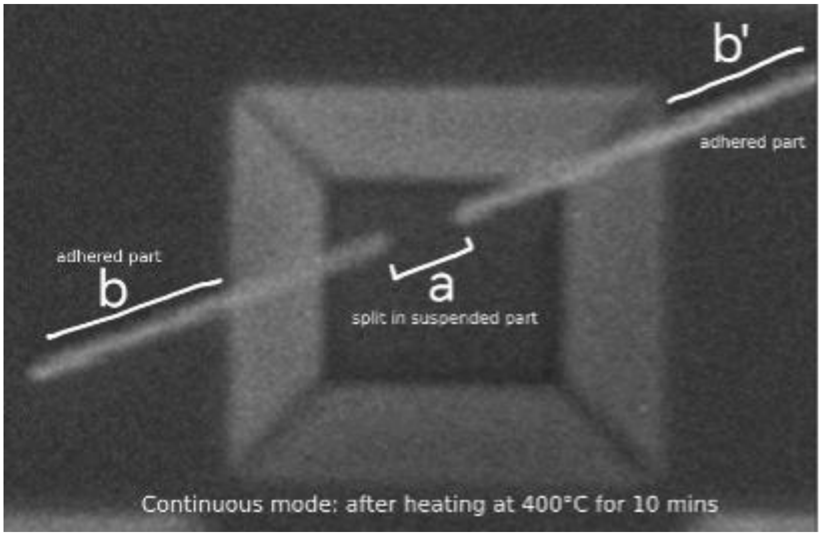

Figure 7. Continuous mode: SEM image of Silver Nanowire over Patterned Si substrate heated until 400°C for 10 mins showing splits in silver nanowire in suspended parts indicated as (a) while they remain intact in adhered parts indicated as (b) and (b')

Whereas, at temperature above 400°C, splitting occurred in both the adhered and suspended parts in the two modes of heat induction which can be seen from point **a** to **c** in Figure 8. Through these overall observations from both sets of experiments and simulations, the distinct response of suspended and adhered parts of silver nanowires on heating enhanced the understanding of the thermal stability and morphological changes occurred in them.

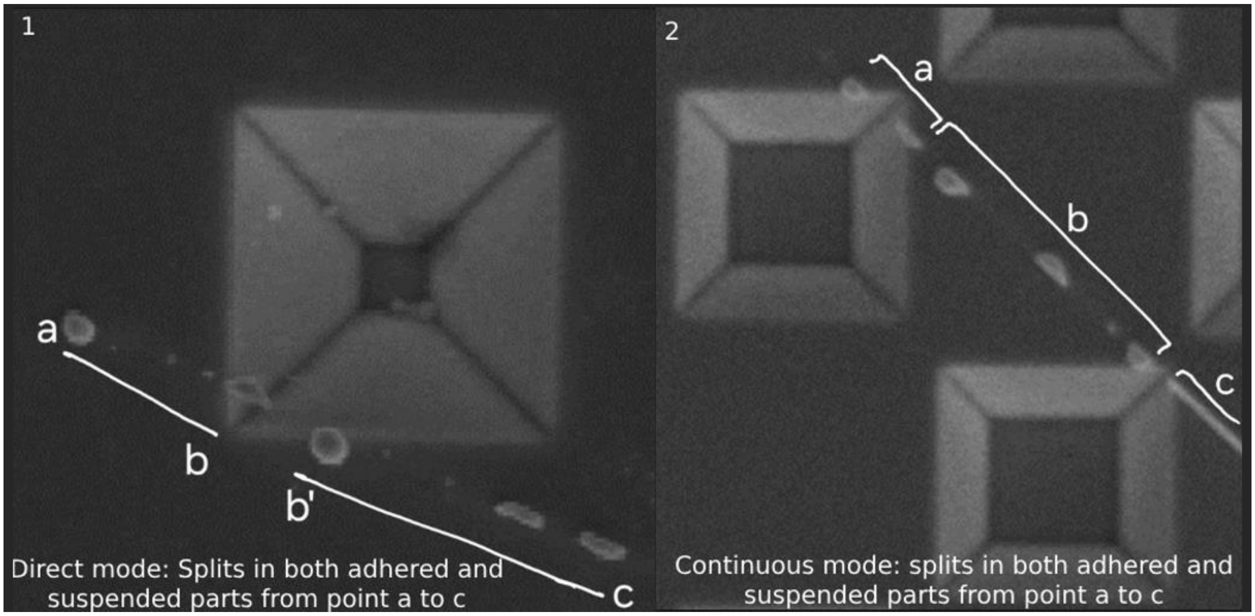

Figure 8. SEM Images 1 and 2 showing splits in both the adhered and suspended parts of silver nanowires at temperature above 400°C. Part a to b and b' to c showed in Image 1, and part b and c in Image 2 is adhered while the part b to b' in Image 1 and part a in Image 2 is suspended part.

4.3 Statistical Analysis

The statistical data regarding heat-induced morphological changes in silver nanowires was gathered through the utilization of Scanning Electron Microscopy (SEM). Initially, the nanowires were meticulously categorized based on their structural configurations, including straight, bent, and crossed formations for the samples from the direct mode of experiments. Later, the data was analyzed based on the number of splits in the adhered vs suspended parts in the silver nanowires. Their lengths and their diameters were measured and averaged to check if thinner nanowires fragments earlier and in cases it completely degrades as in the Figure. 5. The silver nanowire represented as **x** degraded into **x’** resulted in shorter fragmentation of the nanowires due to thinness.

In terms of the measurements of the dimension and statistical analysis of silver nanowires particularly for the total number of splits in the adhered vs total number of splits in the suspended parts, 18 images for the direct mode and 14 images for continuous mode of experiments were finalized. Figure 9. presents greater number of splits in the adhered parts indicated by blue bars whereas lesser number of splits in the suspended parts indicated as orange bars in the direct mode of the experiment in which the heat induction to silver nanowires were directed at 400°C for 10 minutes.

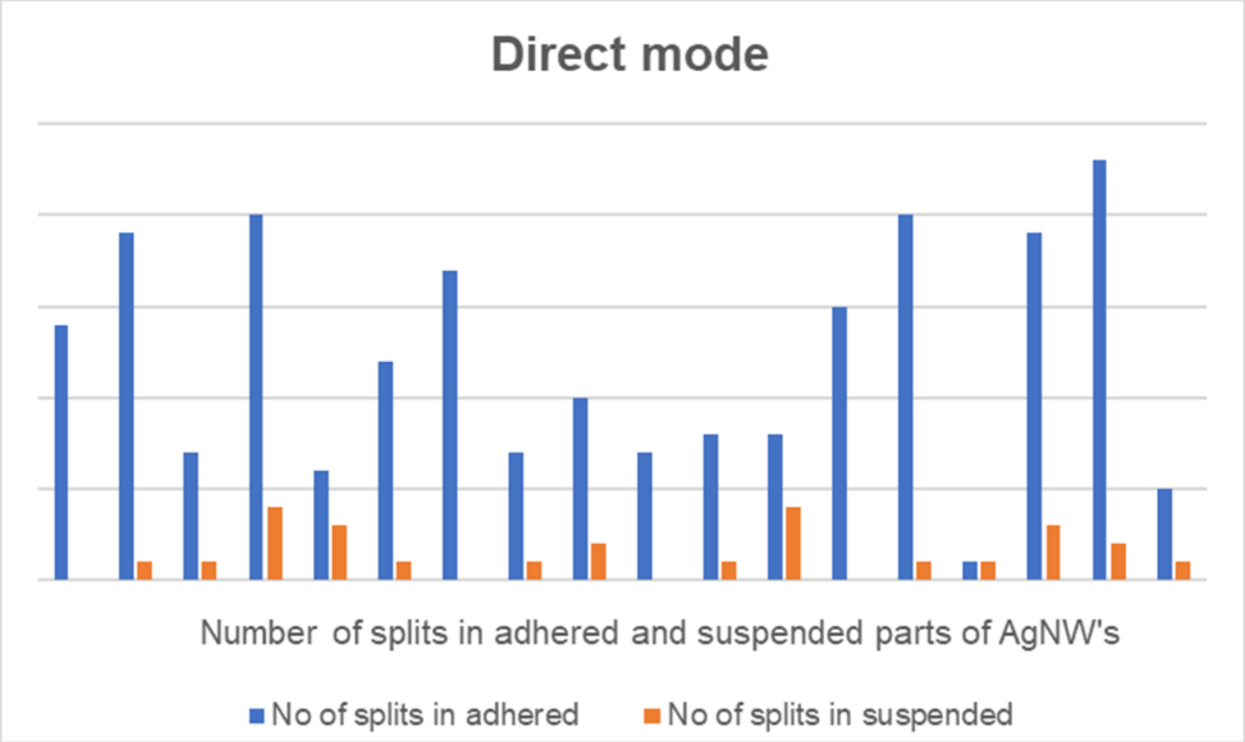

Figure 9. Direct mode: The graphs showing greater number of splits in adhered vs lesser number of splits in suspended parts at 400°C for 10 minutes

While Figure 10. shows the graphical representation of greater number of splits in the suspended vs lesser number of splits in the adhered parts for the temperature increase in cycles of 25°C increment until 400°C for about the time duration of 10 minutes per cycle.

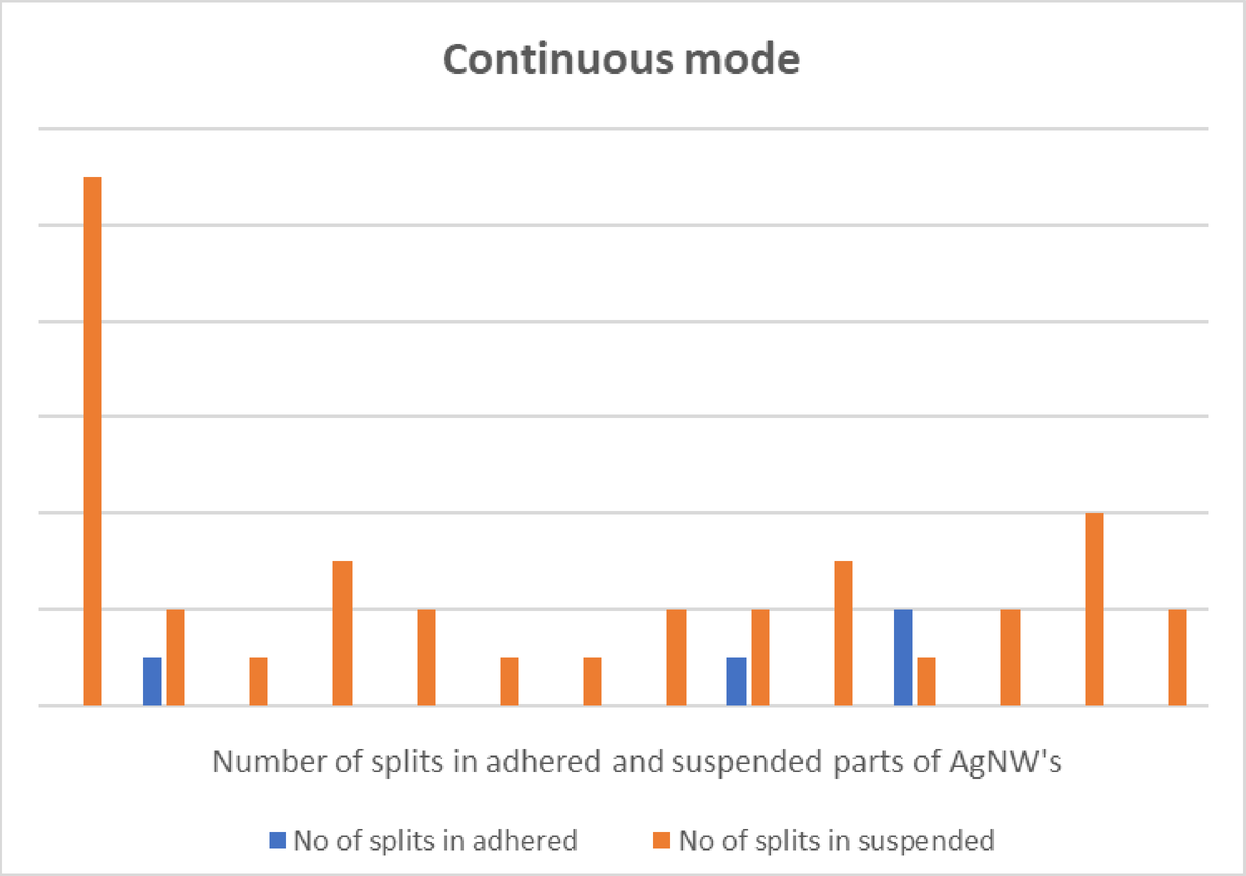

Figure 10. Continuous mode: The graphs showing greater number of splits in suspended vs lesser number of splits in adhered parts until 400°C for 10 minutes per cycle

In the comparison graph shown as figure 11. for both direct and continuous mode of experiments were then visually constructed to depict the distribution of splits between the nanowires, revealing a greater frequency of splits was observed in the adhered portions of the silver nanowires indicated as blue bars in the Direct mode of experiment. The differential splitting behavior between the adhered and suspended portions [1] of the silver nanowires observed during treatment by heat could potentially be attributed to the complex action of mechanical stresses. This outcome underscored the significant response of the nanowires to heat-induced morphological changes, particularly emphasizing the heightened susceptibility of the adhered portions. Overall, this statistical analysis sheds light on the nuanced mechanisms governing the morphological evolution of silver nanowires under thermal conditions, providing valuable insights into their behavior and response to external stimuli.

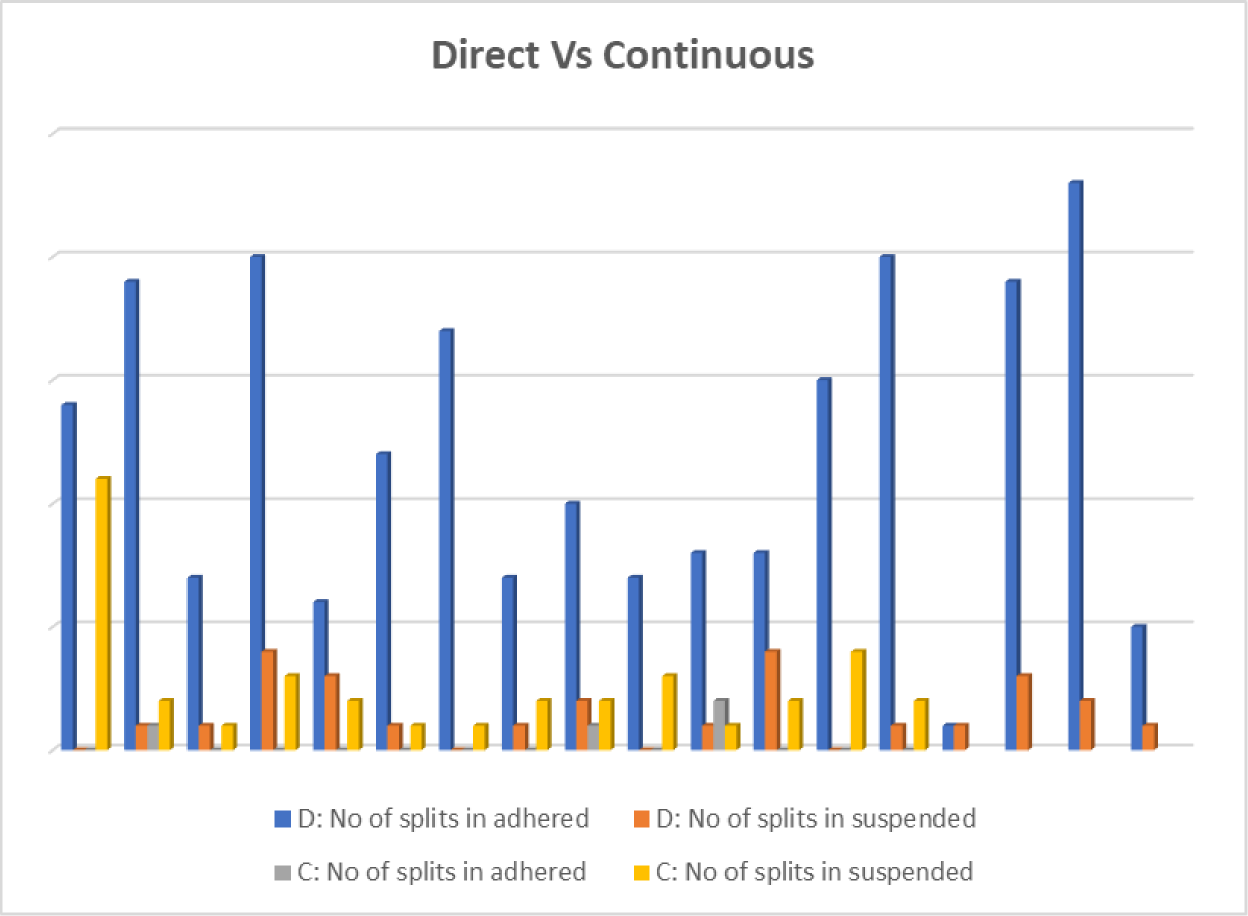

Figure 11. Comparison of Direct Vs Continuous mode showing overall greater number of splits in adhered parts in direct mode while the time is 10 minutes and temperature until 400°C

5. Summary

The main goal of this master's thesis was to find out the morphological changes in silver nanowires upon heat induction. For which there were two sets of experiments performed. The preliminary experiments showed negligible morphological changes in silver nanowires in the form of minor splits. Also, the heat induction in air causes the external contaminants to get in contact with the nanowires which could affect the heat induced morphological changes in the silver nanowires. Thus, keeping the temperature constant and varying the time results in negligible changes in the silver nanowires. So, later experiments performed by my colleague, in which the heat induction was done in a muffled furnace and to distinguish the degradation of silver nanowires the silicon used was patterned silicon substrate which they prepared in Riga by the etching phenomenon. Also, the experiments were performed in two modes of heat induction. In these experiments temperature was high as compared to the preliminary experiments while the time duration was for 10 minutes. One in which heat was induced in the silver nanowires directly at a temperature 400C for 10 minutes was the direct mode whereas in the second mode which is continuous mode the heat induction was in the form of increments of 25C in the timeframe of 10 minutes of cycles with alternative heating and cooling intervals. Both these modes showed completely opposite results which were analyzed by the number of splits in the silver nanowires from statistical analysis. This analysis of the data from these two sets of experiments showed that the majority of the nanowires splits in the adhered parts in the direct mode while suspended parts are not susceptible to heat induction. While at temperature above 400C the splits or aggressive fragmentations in silver nanowires occur in both modes. These behaviors can be attributed to mechanical stresses arising in the nanowires due to the interplay between thermal expansion and frictional forces. The differential splitting behavior between the suspended and adhered parts is influenced by the varying mechanical constraints imposed by their respective positions.

Kokkuvõte

Käesoleva magistritöö põhieesmärk oli välja selgitada hõbeda nanotraatide morfoloogilised muutused nende soojendamisel. Selleks viidi läbi kaks komplekti katseid.

Esialgsed katsed näitasid hõbedaste nanotraatide morfoloogilisi muutusi väikeste lõhede tekkimise kaudu. Samuti põhjustab õhus soojandamine nanotraadi väliste saasteainete kokkupuudet, mis võib mõjutada hõbedaste nanotraatide morfoloogilisi muutusi. Seega põhjustab temperatuuri konstantsena hoidmine ja kuumutamise aja muutmine hõbedasetes nanojuhtmetes tühised muutused. Niisiis, minu kolleegi hilisemad katsed, kus soojendamine tehti summutusahjus ja hõbeda nanotraatide lagunemise eristamiseks kasutati struktureeritud ränisubstraati, mille valmistati Riias söövitamise abil. Samuti viidi katsed läbi kahes soojusinduktsiooni režiimis. Nendes katsetes oli temperatuur kõrgem võrreldes eelkatsetega, samas kui aja kestus oli lühem. Üks, kus soojust indutseeriti hõbedastes nanotraatides temperatuuril 400 °C 10 minuti jooksul, oli otserežiim, samas kui teises režiimis, mis on pidevrežiim, toimus soojusinduktsioon 25 °C sammuna 10-minutilise tsükli jooksul alternatiivsete kütte- ja jahutusintervallidega. Mõlemad režiimid näitasid täiesti vastupidiseid tulemusi, mida analüüsiti statistilise analüüsi hõbedaste nanotraatide lõhede arvu järgi. Nende kahe katsekomplekti andmete analüüs näitas, et suurem osa nanotraatidest jaguneb pinnaga kontaktis olevates osades otserežiimis, samas kui rippuvad osad ei lagune kuumutamise tõttu. Temperatuuril üle 400 C tekivad hõbeda nanotraatides lõhed või mõlemas režiimis. Neid käitumisi võib seostada mehaaniliste pingetega, mis tekivad nanotraatides soojuspaisumise ja hõõrdejõudude koosmõju tõttu. Riputatud ja pinnaga kontaktis olevate nanotraatide erinevat käitumist kuumutamisel mõjutavad erinevad mehaanilised piirangud, mis tulenevad nende vastavatest positsioonidest.

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