Dialectical Observation of Controllable Electrodeposited Ni Nanocones: the Unification of Local Disorder and Overall Order

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Abstract

Dense and ordered Ni nanocones with regular spiral textures had been successfully synthesized via a simple and inexpensive electrodeposition process in the solution containing sodium chloride (NaCl), nickel chloride hexahydrate (NiCl2·6H2O), and boric acid (H3BO3). After analyzing the microstructure, a more optimized possible growth mechanism of Ni nanocones was proposed, in which the growth process was divided into local and global aspects, named multi-dimensional growth mechanism of global order and local disorder. In an area small enough, any subtle state changes would cause disorder of Ni atom arrangement, which made the local microstructure appear disordered, but from a macro perspective, the difference between two adjacent disorders caused by different statuses was too small to be well reflected, only when the difference in state was large enough can the change be observed in the macroscopic appearance, so the global was orderly. Meanwhile, we found that the microstructure of Ni nanocones would be controlled in the electrodeposition solution by adjusting the experiment parameters such as the concentration of NaCl, NiCl2·6H2O, and H3BO3, which indirectly determined the microstructure in a large extent via controlling the generation of intermediate products and the pH.

Keywords: Ni nanocones, Growth mechanism, Electrodeposition, Crystal modifier

Introduction

Nanostructured metals with unique surfaces [1] were widely used in a variety of fields, such as surface modification [2], ultra-hydrophobic layers [3–5], supercapacitors [6], microelectronic interconnection [7], nanoprobes [8], solar cells [9], gas sensors [10, 11], catalysts [12–19], mechanical polishing slurries [20], diamond wheels [21], nanoscale precision surfaces [22, 23]. As a result, many preparation techniques of nanostructured metal surfaces had been proposed, including hydrothermal method [10, 11], sol-gel method [24], template method [25], chemical vapor deposition method [26], chemical reduction method [27], and microemulsion method [28]. However, these traditional methods required a great deal of cost and time [2, 29].

In order to overcome the defects of traditional preparation methods mentioned above, electrodeposition technology has attracted significant research interest and has experienced magnificent developments. It would achieve the target expectation even under the milder conditions for the electric field could increase the reaction rate [2]. The preparation of electrodeposited nanostructured metal surfaces did not require complex auxiliary equipment, which greatly reduced the cost and time. Therefore, a great deal of research had been done on the preparation technology and formation mechanism of nanostructured metal surface topography via electrodeposition [30].
In the specific electrodeposition preparation of nanostructured metal surface, the most representative method was the crystal modifier method [31]. The addition of crystal modifiers could affect the growth direction of crystals, so when reacted with an electrodeposition solution containing a specific crystal modifier, the metal nanostructured surface would grow in a specific direction. Therefore, the use of crystal modifier could easily obtain a specific, close-spaced, and regular 3D nanostructure on the surface of the metal substrate [32].

When a certain amount of ammonium chloride (NH₄Cl), which was the most used crystal modifier, was added to Ni electrodeposition solution, the NH₄⁺ would form complex ions with Ni²⁺ and cause the electrodeposited Ni crystal to grow along (111) crystal face. Therefore, by adding NH₄Cl, it was easy to electrodeposit Ni nanocones that grow in a specific direction on the substrate metal surface and explain this phenomenon more accurately according to the growth mechanism of screw dislocation [33]. Furthermore, nickel, as a good ferromagnetic conductive metal, had the advantages of low price, wide use, and excellent corrosion resistance [34]. Ni nanocones obtained by electrodeposition with solution containing NH₄Cl had important applications in gas-sensitive sensors [10, 11], ultra-hydrophobic surfaces [3–5], and catalysts [12–19].

In this work, we replaced NH₄Cl with NaCl as the crystal modifier and prepared Ni nanocones successfully. Compared with NH₄Cl, NaCl was non-toxic, gentle, and stable. In addition, we put forward the possible specific complex structure and its role in the process of electrodeposition by combining hybrid orbital theory, molecular orbit theory, and actual characterization results. The growth mechanism of Ni nanocones electrodeposited in the solution containing NaCl, which was quite different from common screw dislocation-driven crystal growth mechanism [35], was expounded, and the effects of electrodeposition time and the concentration of NaCl, NiCl₂ and H₃BO₃ on the nanostructure of Ni nanocones were analyzed. Through the analysis of factors affected by the nanostructure of Ni nanocones, the controlled preparation was preliminarily realized, which would be instructive for the preparation of other special-shaped Ni nanocones in the future.

Materials and Methods

Materials

All chemical reagents were analytical pure and could be used directly for chemical reactions. The length, width, and thickness of Ni tablets (cathode and anode) used in our experiment were 70 mm, 25 mm, and 0.08 mm, respectively. Sodium chloride (NaCl), nickel chloride hexahydrate (NiCl₂·6H₂O), boric acid (H₃BO₃), hydrochloric acid (HCl), and anhydrous ethanol (CH₃CH₂OH) were purchased from ChengDu Chron Chemicals Co., Ltd., China.

Surface Treatment and Sample Preparation

In a standard process, two Ni tablets (cathode and anode) were ultrasonically cleaned in deionized water and ethanol, respectively. The cathode Ni tablet was roughened in HCl (25 wt.%, 60 °C) for 30 min. Subsequently, Ni nanocones were electrodeposited on the as-prepared Ni tablets (cathode) from an aqueous solution containing NiCl₂·6H₂O (200 g/L), NaCl (100 g/L), and H₃BO₃ (50 g/L). The temperature (60 °C), current density (0.1 A), and electrodeposition time (20 min) should be regulated and another Ni tablet was employed as the anode to provide Ni ions (Ni²⁺). After the electrodeposition, the cathode was ultrasonically cleaned in deionized water and then ethanol and finally dried in oven for 30 min, respectively. For further comparison, the electrodeposition time was controlled from 5 min to 50 min, and the concentration of NaCl, NiCl₂·6H₂O, and H₃BO₃ was changed from 0 to 167 g/L, 0 to 400 g/L, and 0 to 50 g/L, respectively (Table 1).

Characterization

The scanning electron microscope (SEM) images and corresponding energy dispersive spectroscopy (EDS) were obtained through FEI Inspect F50 (Thermo Fisher, USA) operating at 20 kV. The X-Ray diffraction (XRD) patterns were measured using a D8 advance (BRUKER, Germany) X-ray diffractometer with a Cu Kα radiation (λ = 1.5406 Å). The Fourier Transform infrared spectroscopy (FTIR) pattern was measured using a Nicolet iS 10 (Thermo Fisher, USA) with an ATR module.

Results and Discussion

Determination of Intermediate Products

Usually, when NH₄Cl was used as crystal modifier, the NH₄⁺ would form complex ions with the Ni²⁺ during the electrodeposition process [36]. Therefore, when NaCl was used as a crystal modifier, the solution might produce complex ions, which could promote the conduct of electrodeposition. Figure 1 shows the XRD patterns of electrodeposition solution which were heated and dried with an alcohol lamp (Fig. 1a) and with an oven (60 °C) (Fig. 1b), respectively, and the FTIR pattern of electrodeposition solution (Fig. 1c) after electrodeposition. We could see five different peaks clearly in Fig. 1a, which were NaCl (111), (200), (220), (222), and (400), respectively, compared with XRD standard PDF card. This indicated that the chemical bonds of the target product had been broken after the electrodeposition solution treated at high temperatures (alcohol lamp), in other words, the target product was resistant to poor high-temperature performance. Afterwards, we heated and dried the electrodeposition solution at a lower temperature (60 °C, oven), and the resulting XRD pattern was shown in Fig. 1b. Unfortunately, compared to
the XRD standard PDF cards for all possible compounds, nothing would correspond to these peaks. This suggested that the resulting target product was not a common general compound and might be a rare and special complex. Figure 1c shows the FTIR pattern of electrodeposition solution after electrodeposition, where we could find a peak around 1500 cm$^{-1}$, which was consistent with the characteristic peak (1499 cm$^{-1}$) that the ionic liquid containing Ni halide anion had [37]. Therefore, combined with XRD and FTIR patterns, we considered that some complex ions ([Ni xCly]$^{z-}$), which still presented after the reaction and had poor high-temperature resistance, were generated in the solution during the electrodeposition process.

When Cl$^-$ encountered Ni$^{2+}$ in the solution, Ni$^{2+}$ would be hybridized according to the hybrid orbital theory and form [Ni(H$_2$O)$_2$]Cl$_4$. According to Fernandes et al., when the temperature was above 30 °C, the water molecules would be replaced by Cl$^-$. According to molecular orbital theory, each lone pair of Cl$^-$ did not occupy a single orbit but divided all four orbits equally, the transition from an octahedral complex to a tetrahedral complex occurred [38]. Thus, each lone pair was consistent in both number and energy of occupied orbits, and in theory, the resulting [NiCl$_4$]$^{2-}$ presented a structure of regular tetrahedron in space.

**Effect of Electrodeposition Time and Crystal Modifier**

Figure 2 shows low (Fig. 2a$_1$–c$_1$) and high (Fig. 2a$_2$–c$_2$) magnification SEM images of Ni$_{355}$/Ni$_{370}$/Ni$_{400}$ nanocones with different electrodeposition time (5 min, 20 min, 50 min), XRD and EDS (Fig. 2b$_3$, b$_4$) patterns of typical Ni$_{370}$ nanocones (Fig. 2b$_1$), respectively. It was clear from SEM images that the cathode surface was covered by small and dense plate-like structure through a short electrodeposition time (5 min), and nanocone structures were gradually formed with the increase of electrodeposition time (20 min). With nanocones grown further, the sharp corners were clearer and more textures for longer periods of electrodeposition time (50 min). It was clear from the XRD pattern that there were three different diffraction peaks and all of them were consistent with pure Ni phase with face center cubic (fcc) structure, and no other impurity peaks such as NiO or Ni(OH)$_2$ could be detected. Meanwhile, it was obvious that Ni mainly grew along (220) crystal face. As can be seen from the EDS pattern of typical Ni$_{370}$ nanocones, only Au and Ni could be confirmed, indicating

| Sample | Electrodeposition time (min) | NaCl concentration (g/L) | NiCl$_2$-6H$_2$O concentration (g/L) | H$_2$BO$_3$ concentration (g/L) |
|--------|-----------------------------|--------------------------|-------------------------------------|-------------------------------|
| Ni$_{355}$ | 5                           | 100                      | 200                                 | 50                            |
| Ni$_{370}$ | 20                          | 100                      | 200                                 | 50                            |
| Ni$_{400}$ | 50                          | 100                      | 200                                 | 50                            |
| Ni$_{270}$ | 20                          | 0                        | 200                                 | 50                            |
| Ni$_{437}$ | 20                          | 167                      | 200                                 | 50                            |
| Ni$_{170}$ | 20                          | 100                      | 0                                   | 50                            |
| Ni$_{370}$ | 20                          | 100                      | 400                                 | 50                            |
| Ni$_{320}$ | 20                          | 100                      | 200                                 | 0                             |
| Ni$_{345}$ | 20                          | 100                      | 200                                 | 25                            |

**Fig. 1** The XRD patterns of electrodeposition solution which were heated and dried with an alcohol lamp (a) and with an oven (60 °C) (b). The FTIR pattern of electrodeposition solution (c) after electrodeposition.
that what electrodeposited on the cathode was pure Ni₃₇₀ nanocones without any contamination (Ni was a magnetic material, in order to attenuate magnetically and protect the probe, it needed to be sprayed with gold during SEM characterization).

Figure 3 shows the specific growth mechanism of Ni₃₇₀ nanocones, named multi-dimensional growth mechanism of global order and local disorder. At the beginning, [NiCl₄]²⁻ in the solution moved towards cathode under the action of electric field, Cl⁻ with negative electricality in the [NiCl₄]²⁻ produced repulsive force against electrons on the cathode, whereas Ni²⁺ with positive electricality were attracted to the cathode after entering the diffusion layer. Both repulsive and attractive forces increased significantly, after entering the Helmholtz double layer, the coordinate covalent bonds (Ni–Cl) of [NiCl₄]²⁻ were broken, and then the re-free Cl⁻ (Cl in the broken Ni–Cl bonds) moved against the cathode while the re-free Ni²⁺ (Ni in the broken Ni–Cl bonds) moved towards the cathode. Re-free Ni²⁺ moved in parallel over the cathode and chose the easiest place to attach, usually at the defects and at the steps, for the electrodeposition growth of Ni. Defects (normally, cavate defects and bulging defects) would inevitably occur during the 2D growth of Ni on the cathode, transformed the growth from 2D to 3D (the effects of defects on flat growth was not considered here, but considered the effects on the z-axis direction growth). Ideally, the chances of a new layer growing in each direction caused by a single defect were the same, in other words, the new layer should grow outward in a circular shape (the effects of defects on z-axis direction growth was not considered here, but considered the effects on the flat growth). However, what we saw from Fig. 2 b₂ and c₂ were pyramids rather than circular cones, because the growth of a new layer was still accompanied by a large number of defects that appeared at the frontiers of growth; each defect would make its state differ slightly from the surrounding growth frontiers (a very small range); thus, the resulted Ni nanocone was strictly an N-sided polygonal pyramid, which was called local disorder. Although there were different statuses (growth rate, growth direction, etc.) between two adjacent defects, it was negligible compared to those two defect aggregation points that were far apart. At the macro level, only two defect aggregation points with sufficient status differences that
deserved attention and isolated defects within certain statuses ranges were “merged,” Ni nanocones we observed shown a pyramid (triangular, quadrangular, pentagonal, hexagonal pyramid, etc.), which was called global order (Fig. S1).

**Effect of Components**

In order to further study the specific effect of components in the solution, control variates were used to make preliminary analysis of the surface nanostructure obtained by electrodeposition at different concentrations of...
NaCl, NiCl₂, and H₃BO₃, respectively, and draw corresponding conclusions.

**Effect of NaCl**

Figure 4 shows the low- and high-magnification SEM images of cathode that electrodeposited under different NaCl concentrations at 0 g/L (Fig. 4 a₁ and a₂), 100 g/L (Fig. 4 b₁ and b₂) and 167 g/L (Fig. 4 c₁ and c₂), respectively. When NaCl was not added to the solution, the cathode surface was covered by blocky Ni₂₇₀ nanostructure (Fig. 4 a₁), and although some blocks had a spire-shaped tendency at the apex (Fig. 4a₂), it seemed to be just called undeveloped Ni₂₇₀ nanocones. The reason why it resulted in a large number of undeveloped Ni nanocones on the surface of the cathode was that only NiCl₂ in the solution provided Cl⁻, which made too less Cl⁻ to produce a large number of [NiCl₄]²⁻, and further seriously hindered the generation of Ni₂₇₀ nanocones. When the concentration of NaCl increased (100 g/L), it could be observed that there were still some undeveloped Ni₂₇₀ nanocones (Fig. 4 b₁), but a more pronounced trend of Ni nanocones in some places (Fig. 4b₂). This was because the addition of NaCl in the solution greatly alleviated the lack of Cl⁻, promoted the formation of [NiCl₄]²⁻, but it still could not reach a ratio of 1:4 (n(Ni²⁺):n(Cl⁻)), and the cathode surface was covered by many undeveloped Ni₄₃₇ nanocones. Continuing to increase the concentration of NaCl to 167 g/L, it could be found that most of the cathode surface was covered by Ni₄₃₇ nanocones which made it almost impossible to detect undeveloped Ni₄₃₇ nanocones (Fig. 4 c₁, c₂). The large amount of Cl⁻ in the solution made it possible to produce huge number of [NiCl₄]²⁻, which greatly promoted the generation of electrodeposited Ni₄₃₇ nanocones.

**Effect of NiCl₂**

Figure 5 shows the low- and high-magnification SEM images of cathode that electrodeposited under different NiCl₂ concentrations: 0 g/L (Fig. 5 a₁ and a₂), 200 g/L (Fig. 5 b₁ and b₂), 400 g/L (Fig. 5 c₁ and c₂), respectively. It was clear from Fig. 5 a₁ that the cathode surface was covered by a cotton floc-shaped structure, and the entire surface structure tended to be more densely stacked with Ni balls but no cones structure (Fig. 5a₂). The reason why Ni²⁺ electrodeposited on the cathode in a slow and more average way and caused a cotton floc-shaped structure was that there was no Ni²⁺ in the solution before...
electrodeposition; Ni\(^{2+}\) required for electrodeposition all came from those Ni atoms which lost electrons on the anode, resulting in low concentration of Ni\(^{2+}\) in the solution, so even if there were a large number of Cl\(^{-}\), the generation of [NiCl\(_4\)]\(^{2-}\) was rare, which seriously hindered the formation of Ni nanocones structure. After increasing the concentration of NiCl\(_2\) in the solution to 200 g/L, the electrodeposited cathode surface was covered by some Ni\(_{370}\) nanocones and others undeveloped (Fig. 5 b\(_1\)), the entire surface was rough and fragmented (Fig. 5 b\(_2\)). NiCl\(_2\) added to the solution greatly increased the generation of [NiCl\(_4\)]\(^{2-}\), prompted the formation of Ni\(_{370}\) nanocones, but a part of underdeveloped Ni\(_{370}\) nanocones indicated that the concentration might not have reached the optimal level. When the concentration of NiCl\(_2\) reached 400 g/L, the cathode surface was covered by a large number of huge Ni\(_{570}\) nanocones (Fig. 5 c\(_1\)), some of them presented vaguely visible edges but more conical shapes, and the cone surface was full of texture, with sharp angles and tips pointed to the cone vertex (Fig. 5 c\(_2\), red lines). Theoretically, the concentration of Ni\(^{2+}\) provided by NiCl\(_2\) (400 g/L) was far greater than that desired, which instead highlighted the lack of Cl\(^{-}\); then, a large number of Ni\(^{2+}\) electrodeposited on the cathode during a short period of time resulted in Ni\(_{570}\) nanocones grown too fast to present the local disorder characteristics but emerged cone structure.

**Effect of H\(_3\)BO\(_3\)**

In the series of experiments, H\(_3\)BO\(_3\) was the role of pH regulator, since boron (B) was an electron-deficient atom, it could combine with hydrogen oxygen root ions (OH\(^-\)) from the water molecules, and thereby release hydrogen ions (H\(^+\)) (Eq. 1).

\[
B(\text{OH})_3 + \text{H}_2\text{O} \rightarrow \text{B(OH)}_4^- + \text{H}^+ \tag{Eq. 1}
\]

Figure 6 shows the low- and high-magnification SEM images of cathode that electrodeposited from different H\(_3\)BO\(_3\) concentrations: 0 g/L (Fig. 6 a\(_1\) and a\(_2\)), 25 g/L (Fig. 6 b\(_1\) and b\(_2\)), 50 g/L (Fig. 6 c\(_1\) and c\(_2\)), respectively. In Fig. 6a\(_1\), it could be clearly seen that the cathode was covered with a relatively flat electrodeposition layer, and some areas had slight protrusions (Fig. 6 a\(_2\)), but no Ni\(_{370}\) nanocones structure overall. When there was no H\(_3\)BO\(_3\) in the solution, only electrolyzed water reaction would occur near the cathode, so the solution was generally in an acid-base equilibrium state, and Ni\(^{2+}\) were almost immune to the influence of OH\(^-\) or H\(^+\), resulting in a flat
electrodeposition layer. Adding \( \text{H}_3\text{BO}_3 \) to 25 g/L in the solution, we could observe obvious huge Ni\(_{345}\) nanocones structure from Fig. 6 b1, while the texture trend was complex, the edges and corners were clear (Fig. 6b2). This was due to the addition of \( \text{H}_3\text{BO}_3 \), which supplied more H\(^+\) near the cathode, resulting in a weak acidity environment. When the concentration of \( \text{H}_3\text{BO}_3 \) in the solution reached 50 g/L, the size of Ni\(_{370}\) nanocone was reduced, compared to Ni\(_{345}\) nanocones, but the surface texture was smoother. This was due to the large number of H\(_3\text{BO}_3\), which made the solution appear weak acidic (slightly more acidic than the previous one), the excessive H\(^+\) affected the size of Ni\(_{370}\) nanocones but made the surface more regular.

Overall, the size of Ni nanocones was not proportional relationship to the amount of \( \text{H}_3\text{BO}_3 \) in the solution. This might be that when the solution was free of \( \text{H}_3\text{BO}_3\), the negatively charged OH\(^-\) interfered with the positive electricity Ni\(^{2+}\), which affected the motion of Ni\(^{3+}\). On another hand, when a large amount of \( \text{H}_3\text{BO}_3\) was presented in the solution, a lot of H\(^+\) would attach the cathode surface to generate hydrogen (\( \text{H}_2 \)), but due to the small size of H\(^+\) itself, the influence on the nanostructure of Ni nanocones was quite limited.

**Conclusion**

In summary, we had successfully synthesized Ni nanocones via electrodeposition process in the solution containing \( \text{NiCl}_2\), NaCl, and \( \text{H}_3\text{BO}_3 \). The results have shown that the intermediate product was a special complex, which still presented after the reaction and had poor high-temperature resistance, and that Ni nanocones were pure Ni with fcc structure, grown mainly along (220) crystal face. Moreover, the specific structure of the intermediate product was supported by known mature theoretical systems, the nanostructure and electrodeposition process of the products were investigated, and the probable formation mechanism of Ni nanocones was discussed based on the experimental results. Meanwhile, we found that the nanostructure of Ni nanocones could be controlled by adjusting the experimental conditions such as the concentration of \( \text{NiCl}_2\), NaCl, and \( \text{H}_3\text{BO}_3 \), respectively. Therefore, establishing appropriate parameters was key point for the synthesis of Ni crystals with nanocones structure via this electrodeposition approach. Additionally, we expected that this novel strategy could be possibly extended to some other magnetic metals to synthesize controllable nanocone structure.
Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s11671-020-03321-0.

Acknowledgements

The surface treatment and crystal growth experiments were carried out in Nano Science & Surface Technology Laboratory of Xihua University.

Authors’ Contributions

RZ and JW conceived and designed the experiments. SX and LG performed the experiments and analyzed the data. YL and YW helped in interpretation and discussions. RZ and JW wrote the manuscript. All authors read and approved the final manuscript.

Funding

This work was supported by the National Natural Science Foundation of China (nos. 51602262 and 61871281), the Innovation Fund of Postgraduate of Xihua University (no. ycjc2019033), the Key Project of Natural Science Foundation of Sichuan Provincial Education Department (no. 14ZRA0115), and the “Xihua Scholars” Program of Xihua University (no. DC190007152).

Availability of Data and Materials

The datasets used for supporting the conclusion are included in the article and the supporting file.

Competing Interests

The authors declare that they have no competing interests.

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Received: 26 November 2019 Accepted: 13 April 2020

Published online: 22 April 2020

References

1. Gleiter H (2000) Nanostructured materials: basic concepts and microstructure. Acta Mater 48(1):1–29
2. Lee ML, Jung KK, Lee SH, Ko JS (2016) One-step fabrication of nickel nanocubes by electrodeposition using CaCl2·2H2O as capping reagent. Appl Surf Sci 369:163–169
3. Hönes R, Ruhe J (2018) “Nickel Nanoflowers” with surface-attached fluoropolymer networks by CHI insertion for the generation of metallic superhydrophobic surfaces. Langmuir 34:1–36
4. Salehikahrizsangi P, Raeissi K, Karimzadeh F, Calabrese L, Patane S, Proverbio M (2017) Exceptional piezoresistance coefficient in strained silicon carbide. Chem Chem Phys 16:16711–16719
5. Xiang T, Chen D, Lv Z, Yang Z, Yang L, Li C (2019) Robust superhydrophobic coating with superior corrosion resistance. J Alloys Compd 798:320–325
6. Gao S, Su Y, Wei F, Qi J, Meng Q, Ren Y, He Y (2018) Dandelion-like nickel-cobalt metal–organic framework based electrode materials for high performance supercapacitors. J Colloid Interface Sci 531:83–90
7. Yoon Y, Kim D, Lee J-B (2014) Hierarchical micro/nano structures for superhydrophobic surfaces and super-lyophobic surface against liquid metal. Micro Nano Syst Lett 2:3
8. Lee JM, Lee SH, Ko JS (2015) Influence of open area ratio on microstructure shape in Cu–Ni alloy electrodeposition. Appl Phys A Mater Sci Process 118: 579–585
9. Zhou Y, Sreekala S, Ajayan PM, Nayak SK (2008) Resistance of copper nanowires and comparison with carbon nanotube bundles for interconnect applications using first principles calculations. J Phys-Condens Mat 20: 095209
10. Wang J, Yang F, Wei X, Zhang Y, Wei L, Zhang J, Tang Q, Guo B, Xu L (2014) Controlled growth of conical nickel oxide nanocrystals and their high performance gas sensing devices for ammonia molecule detection. Phys Chem Chem Phys 16:16711–16718
11. Wang J, Yang P, Wei X (2015) High-performance, room-temperature, and no-humidity-impact ammonia sensor based on heterogeneous nickel oxide and zinc oxide nanocrystals. ACS Appl Mater Interfaces 7(6):3816–3824
12. Ye J, Galliardi L, Cristopher JC, Trulhar DG (2017) Single Ni atoms and Ni3 clusters have similar catalytic activity for ethylene dimerization. J Catal 354: 278–286
13. Budi CS, Saikia D, Chen C-S, Koo H-M (2019) Catalytic evaluation of tunable Ni nanoparticles embedded in organic functionalized 2D and 3D ordered mesoporous silicon from the hydrogenation of nitroaromatics. J Catal 370:274–288
14. Wang Y, Zhu Y, Liu Z, Wang L, Xu D, Fang C, Wang S (2019) Catalytic performances of Ni-based catalysts on supercritical water gasification of phenol solution and coal-gasification wastewater. Int J Hydrogen Energ 44(7):3470–3480
15. Li M, van Veen AC (2018) Tuning the catalytic performance of Ni-catalysed dry reforming of methane and carbon deposition via Ni-CoOx interaction. Appl Catal B-Environ 237:641–648
16. Gong W, Jiang Z, Wu R, Liu Y, Huang L, Hu N, Tsaiaraks P, Shen PK (2019) Cross-double dumbbell-like Pt–Ni nanostructures with enhanced catalytic performance toward the reactions of oxygen reduction and methanol oxidation. Appl Catal B-Environ 246:277–283
17. Hassan KE, Kahina D, Turks M, Rekou BH, Anoura A (2019) Enhanced degradation of an azo dye by catalytic ozonation over Ni-containing layered double hydroxide nanocatalyst. Sep Purif Technol 210:764–774
18. Xie X, Chen M, Liu P, Shang J, Liu T (2018) Synergistic catalytic effects of the Ni and V nanoparticles on the hydrogen storage properties of Mg-Ni-V nano-composite. Chem Eng J 347:145–155
19. Long H, Liu X, Xie Y, Hu N, Deng Z, Jiang Y, Wei Q, Yu Z, Zhang S (2019) Thickness effects of Ni on the modified boron doped diamond by thermal catalytic etching for non-enzymatic glucose sensing. Electroanal Chem 832: 353–360
20. Zhang Z, Cui J, Zhang J, Liu D, Yu Z, Guo D (2019) Environment friendly chemical mechanical polishing of copper. Appl Surf Sci 467:4685–11
21. Zhang Z, Wang B, Kang R, Zhang B, Guo D (2015) Changes in surface layer of silicon wafers from diamond scratching. CRP Ann-Manuf Techn 64(1): 394–395
22. Wang B, Zhang Z, Chang K, Cui J, Rosenkranz A, Yu J, Lin C-T, Chen G, Zang K, Luo J, Jiang N, Guo D (2018) New deformation-induced nanostructure in silicon. Nano Lett 18:4611–4617
23. Cui J, Zhang Z, Liu D, Zhang D, Hu W, Zou L, Lu Y, Zhang C, Lu H, Tang C (2019) Unprecedented piezoresistance coefficient in strained silicon carbide. Nano Lett 19:6569–6576
24. Jafari A, Jahromi SP, Boustani K, Goh BT, Huang NM (2019) Evolution of structural and magnetic properties of nickel oxide nanoparticles: influence of annealing ambient and temperature. J Magn Magn Mater 469:383–390
25. Fa D, Yu B, Miao Y (2019) Synthesis of ultra-long nanowires of nickel phosphate by a template-free hydrothermal method for electrocatalytic oxidation of glucose. Colloid Surface A 564:31–38
26. Zanganeh N, Rajabi A, Torabi M, Alahakarami M, Moghaddas A, Sadmehaad MK (2014) Growth and microstructural investigation of multiwall carbon nanotubes fabricated using electrodeposited nickel nanodeposits and chemical vapor deposition method. J Mol Struct 1074:250–254
27. Mehtabi M, Reyhani A, Parvin P, Mortazavi SZ (2019) Catalytic activity of multifunctional carbon nanotubes decorated by nickel nanoparticles based on laser ablation/chemical reduction methods to enhance hydrogen storage properties. Int J Hydrogen Energ 44(7):3812–3823
28. Ni X-M, Su X-B, Yang Z-P, Zheng H-G (2003) The preparation of nickel nanorods in water-in-oil microemulsion. J Cryst Growth 252(4):612–617
29. Wang Y, Zhu Q, Zhang H (2007) Selectected-control synthesis of Hierarchical nickel structures. Mater Res Bull 42(8):1450–1456
30. Rahimi E, Davoodi A, Rashid ARK (2019) Characterization of screw dislocation-driven growth in nickel micro-nanostructure electrodeposition process by AFM. Mater Lett 210:341–344
31. Geng W, Hu A, Li M (2012) Super-hydrophilicity to super-hydrophobicity transition of a surface with Ni micro–nano cones array. Appl Surf Sci 263: 821–824
32. Rahimi E, Rafsanjani-Abbasi A, Imani A, Rashid ARK, Hosseinpour S, Davoodi A (2019) Synergistic effect of a crystal modifier and screw dislocation step defects on the formation mechanism of nickel micro-nanocone. Mater Lett 245:68–72
33. Wang N, Hang T, Shanmugam S, Li M (2014) Preparation and characterization of nickel-cobalt alloy nanostructures array fabricated by electrodeposition. CrystEngComm 16:6937–6943
34. Pathak DK, Chaudhary A, Mishra S, Yogi P, Saxena SK, Sagdeo PR, Kumar R (2019) Precursor concentration dependent hydrothermal NiO nanopetals: Tuning morphology for efficient applications. Superlattice Microst 125:138–143
35. Lee JM, Jung KK, Ko JS (2016) Effect of NaCl in a nickel electrodeposition on the formation of nickel nanosctructure. J Mater Sci 51:3036–3044
36. Hashemzadeh M, Raeisi K, Ashrafizadeh F, Khorsand S (2015) Effect of ammonium chloride on microstructure, super-hydrophobicity and corrosion resistance of nickel coatings. Surf Coat Technol 283:318–328
37. Chinnappan A, Kim H (2012) Nanocatalyst: Electrospun nanofibers of PVDF-Dicationic tetrachloronickelate (II) anion and their effect on hydrogen generation from the hydrolysis of sodium borohydride. Ilt J Hydrogen Energ 37(24):18851–18859
38. Fernandes LC, Correia DM, García-Astrain C, Pereira N, Tariq M, Esperança J Moss, Lanceros-Méndez S (2019) Ionic-liquid-based printable materials for thermochromic and thermoresistive applications. ACS Appl Mater Interfaces 11(22):20316–20324

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