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Electrodeposition and properties of NiW films for MEMS application

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Abstract

The study reports basic investigations on the electroplating and properties of movable NiW microstructures with potential application in MEMS as temporary contacts for IC integration. The NiW layers have been deposited from nickel sulphamate electrolyte (MICROFAB NI-110, Enthone GmbH, Germany) with addition of citric acid stabilized tungsten complex at operating temperature of 50 °C and pH of about 3.0 using direct und pulse current plating regimes. The influence of the electroplating parameters, such as the tungsten concentration in the electrolyte and the current density on the tungsten content in the electroplated alloy, the surface structure and morphology of the deposits, as well as the mechanical properties of the alloy have been thoroughly investigated. The process allows deposition of 12 μ m thick homogeneous NiW layers. An essential improvement of the mechanical properties such as micro hardness, elasticity and internal stress compared to that of the pure nickel has been achieved at comparatively low tungsten content of 3.2 wt.%. © 2005 Elsevier Ltd. All rights reserved.

Keywords: NiW; Electrodeposition; MEMS

1. Introduction

The electro deposition of nickel and different Ni alloys is a process of essential importance as these materials have broad and expanding technical and industrial application. Nickel and its alloys with elements such as iron, cobalt, phosphor or tungsten are especially appropriate for usage in the field of micro electromechanical systems (MEMS) where microstructures with high mechanical strength and wear resistance coupled with high thermal resistance and stability against plastic deformation are required. By choosing a proper alloying element the mechanical features of the alloys can be essentially influenced, the properties of predominant interest can be improved and thus, tailored alloys can be electroplated. It is known that nearly all electroplated nickel alloys possess higher mechanical hardness and tensile strength compared to the pure nickel but also an increased brittleness and internal stress [1]. Some metallic alloying elements, such as cobalt increase the hardness by formation of mixed crystal systems in which the nickel atoms and the atoms of the alloying component are uniformly distributed. Other alloying elements such as phosphorus or tungsten deteriorate the formation of the crystal lattice and as a result, nanocrystalline alloys or amorphous films known also as metal glasses can be deposited. Usually, the increase in the hardness is accompanied by a decrease in the grains size and the crystal dislocations in the electroplated alloy [1,2]. The hardening of the nickel alloys by the elements from the first group, e.g. by formation of mixed crystal lattice, is rather limited. Once the maximum value of about 450 HV is achieved, the further variations of the alloying element content and the electroplating parameters have negligible effect on the alloy hardness [3]. Much harder nickel alloys can be deposited if the alloying elements from the second transition group are used. Tungsten is known to be the best hardening element for the nickel alloys. The main problem concerning the NiW electrodeposition is that the ions of both elements, nickel cations Ni^{2+} and tungstate anions WO_4^{2-} , respectively, are very sen-

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sible to pH of the solution and cannot be mixed in any desirable concentration in aqueous electrolytes. In acidic media, tungsten forms solid tungstate and polytungstate acid and it is very difficult to dissolve back the precipitate obtained. On the other hand, in alkaline media Ni precipitates as nickel hydroxide [4]. Thus, during NiW electroplating one of both precipitates can be easily formed depending on the local pH value, unless proper complex agents are added in the solution. It is well known that ammonium form complexes with Ni²⁺, while citric acid stabilises the tungstate anions and can form mixed complexes with both metal ions [5]. These two compounds most often present in the electrolytes used for NiW electroplating as, depending on the pH one of them is always in much higher concentration.

The common electrolytes for NiW electroplating use nickel sulphate and sodium tungstate as metal precursors. They have alkaline pH and contain high concentration of ammonium and oxalic acids. The concentration of tungsten can vary considerably reaching up to 85 wt.% [6]. The alloys deposited from these electrolytes may contain up to 70 wt.% W and their hardness is three to four times higher than that of the pure Ni [2,6–8]. However, these electrolytes are not environmentally friendly due to the high concentration of ammonium. In addition, the range of the optimal electroplating parameters for these electrolytes is very narrow. The required process temperatures of 85-90 °C and pH values of 8-11 are too high for fabrication of microstructures on Si-wafers via the processes used in the microsystem technology. In a previous study, it has been shown that if such an electrolyte is used at the operating temperature of 40 °C, NiW microstructures containing up to 22 wt.% W and a hardness two times higher than that of the pure nickel can be fabricated. Unfortunately, the deposited layers were brittle, had high internal stress and cracked easily with the increase of the thickness, which excluded their usage for microsprings fabrication [6]. Alternative electrolytes for NiW electrodeposition are the nickel sulfamate electrolytes [9-15]. The main advantages of these electrolytes are the moderate plating temperatures (about 50 °C) and pH (near neutral), the lack of ammonium, as well as the ability to produce homogeneous films with increased hardness and reduced internal stress. These properties are especially attractive for application in the field of MEMS and justified our choice of NiW electroplating bath.

The recent paper reports basic results on electroplating and properties of NiW microstructures deposited from a modified commercial nickel sulphamate electrolyte. The envisage application of these microstructures, namely as movable contacts in the field of MEMS, requires high hardness and wear resistance of the deposited NiW films, as well as low stress, high elasticity and flexibility, combined with relevant current yield of the electroplating process. The research was concentrated on the effect of the experimental variables on the composition of the deposited alloy. The tungsten concentration in the bath and the current density were systematically changed in the ranges within which they affect the composition of the alloy without causing high internal stress and cracking of the deposited layers. The crystal structure, the surface morphology and the mechanical properties such as microhardness, Young's modulus and elastic behaviour were investigated as a function of tungsten content in the alloy.

2. Experimental

The nickel-tungsten electroplating bath was prepared from a commercial nickel sulfamate electrolyte containing 80 g/l Ni as nickel sulfamate concentrate (MICROFAB NI-110, Enthone GmbH, Germany), 4.2-20 g/l W as a citric acid stabilized tungstate complex prepared from Na₂WO₄·2H₂O and C₂H₈O₇, and 30 g/l H₂BO₂. The concentration of tungsten was varied in the range 5-20 wt.%. Four electroplating baths with tungsten concentrations of 4.2, 8.9, 14.1, 20.0 g/l were used. These concentrations of tungsten, C_{W}^{E} , correspond to 5, 10, 15 and 20 wt.% W, respectively. The concentration of the metal ions was monitored using inductive coupled plasma spectrometer (ICP) model Atom Scan 16/25 (Thermo Instruments Systems Inc., USA). The electrolyte was refreshed periodically to avoid the depletion of the metals. The operating temperature of the bath was 50 °C and pH was in the range of 2.4-3.2. The electrolyte was circulated using a centrifugal magnetic pump.

The microsprings were fabricated using the surface micromachining technology including photolithography, evaporating metallization, electroplating and sacrificial layer etching. Oxidised 100 mm silicon wafers were used as substrates. A plating base consisting of 50 nm thick titanium and a 100 nm thick copper layer was evaporated on the polished side of the wafer. A sacrificial 50 μ m thick copper film was electroplated from CUBATH SC electrolyte (Enthone, GmbH, Germany) at current density of 15 mA/cm². After a photolithography step the NiW micro springs with thickness of up to 12 μ m were deposited. The deposition was performed under direct current plating (DC) condition or in a symmetrical pulsing (PC) mode with $T_{on} = T_{off} = 5$ ms using pulse plating equipment Dynatronix, Type DPR-20-5-10 and an insoluble anode. The mean current density was varied in the range 5–20 mA/cm².

The surface profile and the thickness of the electroplated layers were measured using a Tencor PA-10 profiler. The surface morphology was investigated by scanning electron microscopy (SEM) using a ZEISS GEMINI 982 microscope. The nickel and tungsten contents in the electrodeposited samples and their surface topography were determined by energy dispersive X-ray spectroscopy (EDX) in a scanning microscope mode. The crystal structure of the alloy was investigated by X-ray diffraction (XRD) technique using a Philips diffractometer (Cu K α radiation) Model PW 3010. The Vickers microhardness of the electroplated microstructures was measured with SHIMADZU HMV-2 micro hardness tester using a 25 g load.

For determination of the Young's modulus single-clamped NiW-cantilevers were electroplated from electrolytes with different tungsten concentration. The dimensions of these



Fig. 1. Experimental set up for the bending tests.

cantilevers were as follows: width of 100 μ m, length of 600–800 μ m and thicknesses of about 12 μ m. The Young's modulus values were determined using a home-made bending set-up [11] which is schematically shown in Fig. 1. The samples, clamped between two glass plates, were adjusted on a weighing machine measuring the contact force with a resolution of 50 nN and a display accuracy of 10 nN. The weighing machine was mounted on an x/y-stage with 1 μ m displacement resolution. A stylus was imprinted on the cantilever surface causing the bending by means of a linear motor with a step width of minimum 100 nm. Two force–deflection curves were measured on each cantilever as the distances from the fixation point were $l_1 = 300 \,\mu$ m and $l_2 = 450 \,\mu$ m. The calculated spring stiffness c_1 and c_2 were used to determine the Young's modulus *E* according Eq. (1)

$$E = \frac{4\Delta l^3}{bt^3} \left(\sqrt[3]{\frac{1}{c_2}} - \sqrt[3]{\frac{1}{c_1}} \right)^{-3}$$
(1)

where Δl represents the distance between the measuring points 1 and 2, *b* the width and *t* is the thickness of the measured beam. Stress and strain values were calculated using Hook's law according Eqs. (2) and (3):

$$\sigma_{\rm b} = \frac{6Fl}{bt^2} \tag{2}$$

$$\varepsilon = \frac{\sigma_{\rm b}}{E} = \frac{3}{2} \frac{ft}{l^2} \tag{3}$$

where F is the applied force and l is the distance from the fixation point.

3. Results

The influence of tungsten concentration in the electroplating bath on the current yield, η , respectively on the deposition rate, R_d , of the DC and PC plating at mean current density of 10 mA/cm² is presented in Fig. 2. The data for each point were obtained as an average value from three experiments. It can be seen that in both plating modes the Faradaic effi-



Fig. 2. Dependence of current yield/deposition rate on the tungsten concentration in the electrolyte at mean current density of 10 mA/cm^2 in DC and PC electroplating modes.

ciency decreases with the increase of C_W^E , however at pulsing current mode it is slightly higher in the whole range of tungsten concentrations tested. The PC electroplating mode has been used for the rest of the tests presented in this work. The current yield in the bath containing 5 wt.% W (4.21 g/l) is relatively high (70%) but the efficiency of the process decreases rapidly with the increase in tungsten concentration. At $C_W^E = 20$ wt.% (20 g/l) it drops to 17 and 12% for pulse and direct current mode, respectively. The corresponding values of the deposition rate are 36 and 25 nm/min, which is nearly an order lower than the deposition rate of 205 nm/min typical for the MICROFAB NI-110 bath.

The applied current density, *j*, itself affects essentially the efficiency of the process. This effect is illustrated in Fig. 3 for electroplating baths containing 15 and 20 wt.% W. The current yield increases linearly with the increase in current density. For the 15 wt.% W electrolyte η is only 7% at 5 mA/cm² but it reaches 56% at 20 mA/cm². The values of the current yield in the electrolyte containing 20 wt.% W are somewhat lower in the whole range of current densities tested but the linear correlation between η and *j* does not change.

The composition of the deposited alloys also depends strongly on the current density of the electroplating. This



Fig. 3. Dependence of current yield on the mean current density in PC electroplating mode.



Fig. 4. Influence of current density on the tungsten content in the layers deposited in PC electroplating mode.

effect is presented in Fig. 4 for the electrolytes with 15 and 20 wt.% W. The results show that the content of tungsten in the deposited layers, C_W^L , decreases essentially with the increase in current density. The alloy deposited from the 15 wt.% W bath at current density of 5 mA/cm² contains 4.87 wt.% W, while at 20 mA/cm² C_W^L drops down to only 0.41 wt.% W. The corresponding values of the sample deposited from the bath containing 20 wt.% W are higher, 6.13 and 0.83 wt.% W, respectively as the trend is very similar.

The visual inspection of the samples electroplated at all current densities showed homogeneous and metallic bright surfaces. The scanned surface profiles however, registered a gradual increase of the roughness with the increase of current density. The average roughness factor, R_a , of the samples deposited in 20% W electrolyte was about 50–65 nm at $j = 5 \text{ mA/cm}^2$, while at $j = 20 \text{ mA/cm}^2$ it increased with more than an order of magnitude and reached 700–800 nm. The



Fig. 5. SEM images of NiW layers deposited in PC mode at varying current densities from a bath containing 20 wt.% W.



Fig. 6. Dependence of Vicker's microhardness on the tungsten content in the deposited layer.

changes in surface structure with the applied current density, respectively with the deposition rate, can be seen in Fig. 5 which shows SEM images of samples deposited from the electrolyte containing 20 wt.% W at current densities varying in the range 5–20 mA/cm². A clear tendency of increasing the size of the grains with the increase of η is observed. The surface morphology changes from fine globular grains with homogeneous distribution to comparatively rough polycrystalline structures.

The tungsten content in the electroplated films deposited at mean current density 10 mA/cm^2 depends linearly on the tungsten concentration in the bath as $C_W^L = 0.16C_W^E$. Fig. 6 presents the data for the measured Vickers hardness of the corresponding specimens as an average value of five measurements. The trend of the microhardness follows that of C_W^L and increases with the increase of tungsten concentration in the plating bath.





Fig. 7. SEM images of NiW samples with different tungsten content (shown on the micrographs) form electrolytes with varying W concentration at mean current density of 10 mA/cm^2 .



Fig. 8. XRD spectra of NiW layers with different tungsten content deposited at current density of 10 mA/cm² in PC mode.

The SEM images of the NiW alloys deposited from baths with different C_W^E at mean current density of 10 mA/cm² are presented in Fig. 7. The SEM images demonstrate smooth topography with globular compact grains. No cracks are visible on the surface. The more tungsten contains the specimen, the smaller are the crystal grains and the more homogeneous is the surface of the deposit.

In Fig. 8 are depicted the $\theta/2\theta$ XRD spectra of the same samples. They show comparatively low integral intensity, suggesting a micro cristallinity of the electroplated NiW layers. Yet, the characteristic peaks corresponding to nickel fcc crystal lattice are clearly depicted and are labelled by their Miller indices. The difference in peaks intensity and width is distinct enough in order to calculate the size of the crystallites using the Sherrer equation [16]. The obtained data are summarized in Table 1.

Fig. 9 shows the design in top view of the fabricated microsprings. The Young's modulus of structures from that





Fig. 9. Design in top view of the fabricated microsprings.



Fig. 10. Stress–strain diagrams of the fabricated structures as a function of tungsten content in the deposited layer.

type, deposited from electroplating baths with varying C_{W}^{E} at mean current density of 10 mA/cm² were measured according the previously described procedure. The calculated data depended extremely strong on the thickness of the cantilevers. At the same time the measured thickness showed a variation of $\pm 1 \,\mu$ m over the beam length. In addition, sporadic pits were visible on some cantilevers. In order to compensate these effects, the obtained strain–stress curves were fitted by varying the experimentally determined mean thickness of the cantilevers by maximum $\pm 0.6 \,\mu$ m (see Eq. (1)) and are plotted in Fig. 10.

 Table 1

 Peaks intensity and crystallite size obtained by XRD spectra

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$\overline{C_{\mathrm{W}}^{\mathrm{L}}}$ wt.%	Peak intensity (I_p) ; peak position (2θ)				Relative intensity $I_p / \sum I_p^i$		Crystallite size (nm)	
	(1 1 1)	$\langle 200\rangle$	$\langle 220\rangle$	(311)	(111)	$\langle 200\rangle$	(111)	$\langle 200\rangle$
0	900,0000; 44.53	6593,0000; 51.87	1528,0000; 76.41	262,0000; 92.97	0,09695142	0,71022299	34.2	33.8
0.65	2530,0000; 45.9	3457,0000; 51.95	2172,0000; 76.45	388,0000; 93.2	0,2960103	0,4044694	31.8	28.9
1.44	795,0000; 44.29	279,0000; 51.71	219,0000; 76.25	188,0000; 92.93	0,66139767	0,23211314	25.6	15.3
2.30	1576,0000; 44.43	445,0000; 51.81	296,0000; 76.45	228,0000; 92.87	0,61925344	0,17485265	18.9	12.4
3.21	841,0000; 44.45	240,0000; 51.85	225,0000; 76.43	164,0000; 92.97	0,57210884	0,16326531	12.8	10.7
5.41	0+1,0000,44.45	240,0000, 51.85	223,0000, 70.43	104,0000, 92.97	0,57210864	0,10520551		12.0

4. Discussion

The electroplating baths used in this study are based on the standard nickel sulfamate electrolyte, which contains 80 g/l nickel. The high metal content ensures an excellent electro conductivity of the bath, which in turns improves both the homogeneity of the deposits and the current yield of the process. These features are typical for MICROFAB NI-110 and make the electrolyte especially suitable for fabrication of microstructures, which determined our choice of the plating bath. The current yield of the MICROFAB NI-110 electrolyte is 97%. The tungsten was added as citric stabilised complex ions as neither tungsten nor nickel ions in the as-prepared mixed electroplating solution showed a tendency to precipitate. The gradual increase of tungsten concentration has a reverse effect on the efficiency of the process and the current yield, respectively the deposition rate, drops essentially with the tungsten enrichment of the electrolyte to reach a value of 17% at $C_{\rm W}^{\rm E} = 20$ wt.% (20 g/l) for the PC plating. In accordance with the literature data the η values for DC mode are even lower [17]. As far as very low deposition rates are not appropriate from technological point of view, the tungsten concentration in the plating bath was not further increased and the rest of the tests were performed in a PC plating mode. The observed drastic decrease of the current yield with the increasing tungsten concentration in the bath and the registered low values of η are not surprising. According to the available literature, the Faradaic efficiency of NiW electroplating usually does not exceed 12-14% and alloys with high tungsten content, never mind the exact composition of the plating bath, can be deposited mainly in the cost of decreasing the corresponding Faradaic efficiency [18,19]. These effects are typical for electroplating of metals such as tungsten, which cannot be deposited from aqueous solutions unless a second metal from the iron group such as Ni is present in the electrolyte. The phenomenon is known as induced co-deposition and its detailed mechanism is still not fully understood. The most widespread hypothesis assumes that the NiW alloy deposition is a result of two main cathodic reactions, namely a reduction of nickel ions (usually as ammonium complexes) and a depolarization of tungsten or/and mixed nickel-tungsten complexes (usually of oxalic acids, such as the citric acid), which proceed simultaneously [5,20]. According to other authors deposition of NiW alloy from nickel sulfamate electrolytes is a result from the inclusion of metallic tungsten or tungsten anions in the already formed nickel matrix [21]. As far as tungsten and hydrogen have very close redox potentials, depending on pH of the bath a more or less intensive side reaction of hydrogen evolution always takes place on the cathode as well [15,22]. In addition, tungsten is a very good catalyst for hydrogen evolution [23] and its deposition on the cathode accelerates the side cathodic reaction leading to the observed reverse dependence between $\eta(R_d)$ and C_W^{E} . At equal concentration of tungsten in the bath the Faradaic efficiency increases linearly with the increase in the current density (Fig. 3), while the

EDS analysis of the corresponding alloys showed a reverse dependence of tungsten content in the deposit on the current density (Fig. 4). The letter fact disagrees with the observation of other authors for NiW deposition from neutral electrolytes with high tungsten content [19,24]. However, it should be taken into account that firstly, the electroplating bath used in this research is acidic and therefore, rich of hydrogen ions and secondly, the C_{W}^{E} is much lower than that of nickel and the tungsten deposition most probably proceeds under diffusion control. The results obtained imply that the registered increase of η , respectively of the deposition rate with *j*, is due to a favoured reduction of nickel ions in the bath. At the same time, the reduction of the tungsten and/or the mixed nickel-tungsten citrate complex ions is depressed due to intensification of the side reaction of hydrogen evolution, which is facilitated by the low pH of the electrolyte.

The tungsten content in the deposited alloys affects strongly the surface topography. The layers fabricated at mean current density of 5 mA/cm^2 have maximal tungsten content and very fine homogeneous surface with spherical, compact and smooth grains. The increase in current density reduces the tungsten content in the alloy, which in turns causes gradual increase of the grains size and transformation of the fine spherical nodules in rather rough and disordered structures.

The mean current density of 10 mA/cm² was considered as a reasonable compromise with respect to η and $C_{\rm W}^{\rm L}$. It was used to investigate the dependence of tungsten content in the alloy on its concentration in the electroplating bath. Again, in order to avoid too low current yields, C_{W}^{E} was varied in comparatively narrow range (4.2-20 g/l). The observed distinct linear enrichment of tungsten in the deposited alloy with the increase of C_{W}^{E} shows that the share of the second main cathodic reaction, including the reduction on of tungsten complexes is enhanced proportionally to the increase of tungsten concentration in the bath. The results obtained suggest fast discharge of tungsten complex ions on the cathode and diffusion control of the process. The maximum tungsten content achieved was 3.21 wt.% W, which is rather low in comparison to the values obtained in other electrolytes [5,13,20]. Nevertheless, the enrichment of alloy with tungsten even at these low concentrations leads to essential hardening of the alloy (Fig. 6). The trend of the microhardness follows that of the $C_{\rm W}^{\rm L}$ and increases linearly with $C_{\rm W}^{\rm E}$. The maximal value of 730 ± 11 HV 0.025 obtained for the sample with highest tungsten content is about 2.5 times higher than that of the pure nickel. The strong influence of tungsten on microhardness is combined with essential changes in surface structure and morphology of NiW alloy (Fig. 7). The more tungsten contains the specimen, the smaller are the crystal grains and the more homogeneous is the surface of the deposit. Such an effect has been reported by other authors, although for NiW alloy much richer of tungsten [25]. However, our results are entirely reasonable, as it is well known that usually, the hardening of the alloy is most pronounced during the initial inclusion of the alloying element in the main metal matrix. It should be noted that the observed changes in the surface structure and morphology with the increase in tungsten content as a result of $C_{\rm W}^{\rm E}$ rising and those caused by the varying current density (Fig. 5) are in good agreement.

The $\theta/2\theta$ spectra in Fig. 8 show relatively low integral intensity with well depicted peaks characteristic for a face centred cubic crystal lattice of isotropic nickel. The spectrum of the pure nickel sample is dominated by the (200)peak. The intensity of this peak decreases with the increasing tungsten content, accompanied by slight increase in the relative intensity of the $\langle 1 1 1 \rangle$ peak. The changes in the other two peaks are negligible. As a whole the intercalation of tungsten atoms in the nickel crystal lattice does not change much the crystal orientation in the deposited layers. However, the enrichment of the alloy with tungsten leads to essential decrease in the size of the crystallites as can be seen from the data in Table 1. The crystallites decrease systematically with the increase of the tungsten content. A very good correlation between the data calculated from the full width of the half maximum (FWHM) of (111) and (200)peaks is obtained. These results are in accordance with the SEM images of the samples showing change of the surface structure in direction to lower micro crystallinity with the tungsten enrichment of the alloy. They correlate well with the registered strong increase in the micro hardness of the investigated samples, as it is well known that the hardenning of alloys generally is accompanied by a decrease in grains size [1,2].

The fitted curves in Fig. 10 show a linear increase of the strain with the increasing stress. The measured Young's modulus of the cantilevers electroplated from the nickel bath is comparable to that obtained earlier by micro tensile testing [26] and resonating beam experiments [27]. The slope of the curves, which represents the Young's modulus, is nearly constant for all samples with a value of about 180 GPa. At a certain stress the samples deform plastically which results in decrease of the slope values. The plastic deformation occurs at higher stress values at microstructures with higher tungsten content, indicating a distinct favourable effect of tungsten on the alloy elasticity. The values of yield strength, R_{p02} increase correspondingly, as can be seen from the data included in Fig. 10. The elastic behaviour of the material under study correlates well with the registered increase of the micro hardness and the rule that a doping element, which increases the hardness of the material under investigation, also increases its yield and tensile strength. The improvement in the elastic behaviour can be explained by the grain size and the texture effects in the deposited layers. It is a common experience in material engineering that metals with smaller grain sizes show less ductility compared to those with high grain sizes. They possess a higher concentration of grain boundaries, which when being plastically deformed are obstacles for the slipping of the atomic layers.

5. Conclusions

Moveable microstructures with application as temporary contacts in IC integration were fabricated by electroplating of NiW layers from nickel sulfamate electrolyte doted with citric acid stabilised tungstate complexes. An essential improvement of the mechanical properties such as higher hardness, lower stress and improved elastic behaviour comparing to the pure nickel was achieved at comparatively low tungsten content of 3.2 wt.%. It was shown that the increase of tungsten content can be realised either through increasing the tungsten concentration in the bath or by usage of very low current densities. The former approach leads to essential decrease of the current yield. Much higher Faradaic efficiencies can be achieved by increasing the current density, which however, has a reverse effect on the tungsten content in the deposited layer. If low current densities are used, the time required for deposition of films with a defined thickness must also be prolonged. Therefore, none of these both approaches is ideal. As a result of the research performed, the electroplating of NiW microstructures from a bath with $C_{\rm W}^{\rm E} = 14.1 \, \text{g/l} (15\%)$ at current density $j = 10 \, \text{mA/cm}^2$ is recommended as an optimal compromise at the time being. A further research is in progress, aimed to improve the deposition efficiency by optimisation of the pulsing current mode and to elucidate the exact mechanism of the electroplating process.

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