NOVEL APPROACH TO PRODUCE NANOPATTERNED TITANIUM IMPLANTS BY COMBINING NANOIMPRINT LITHOGRAPHY AND REACTIVE ION ETCHING

M. Domański[1,2], R. Luttge[1], E. Lamers[3], A.J.A. Winnubst[2], X.F. Walboomers[3], J.A. Jansen[3] and J.G.E. Gardeniers[1]

[1] Mesoscale Chemical Systems, MESA+ Institute for Nanotechnology, University of Twente, NETHERLANDS
[2] Inorganic Membranes, MESA+ Institute for Nanotechnology, University of Twente, NETHERLANDS
[3] Departament of Biomaterials, Radboud University Nijmegen Medical Centre, NETHERLANDS

ABSTRACT

Nanofeatures may enhance biofunctionality in implants, leading to a new generation of biomaterials with bone regeneration activity. To proof this hypothesis, we developed a nanofabrication method to achieve highly ordered nanoscale surface patterns on medical grade titanium. Thermal nanoimprint lithography and chlorine-based inductively-coupled plasma reactive ion etching were combined to produce nanogratings with smallest ridge- and groove feature sizes in the order of 150 nm. Silicon NIL stamps were fabricated using laser interference lithography and cryogenic inductively-coupled reactive ion etching in silicon with an aspect ratio (height to groove width) of 2.5 for the smallest grating pitch of 300 nm.

KEYWORDS: Nanostructures, biofunctionality, titanium nanofabrication

INTRODUCTION

Titanium as a biomaterial was successfully used already for several decades. In recent years the variety of titanium surface modification methods has grown enormously. These surface modifications are meant to induce better implant performance by introducing either regular or random topographies [1-2]. In order to investigate the effect of size of such features in titanium, a technology is needed to systematically nanopattern its surface by lithography.

Figure 1 demonstrates, for example, a cell culturing assay on polystyrene substrates replicated from a master produced by Laser Interference Lithography (LIL) and Reactive Ion Etching (RIE). Such fabrication processes capable of delivering large uniformly patterned areas with nanostructures of up to 5 cm^2 are valuable for the variety of biological assays required to explore the influence of nanostructure on living organisms. Based on these previous cell alignment studies by us [3], the aim now was to fabricate ridges with a ridge-to-groove width ratio of 1:1 in titanium implants, however by the very nature of designing a fabrication process, still deviations of these targeted ratios exist. In this work we report for the first time a process to create periodical nanogratings into the surface of large substrates of medical grade titanium suitable the fabrication of implants for statistical studies *in vitro* and *in vivo*.

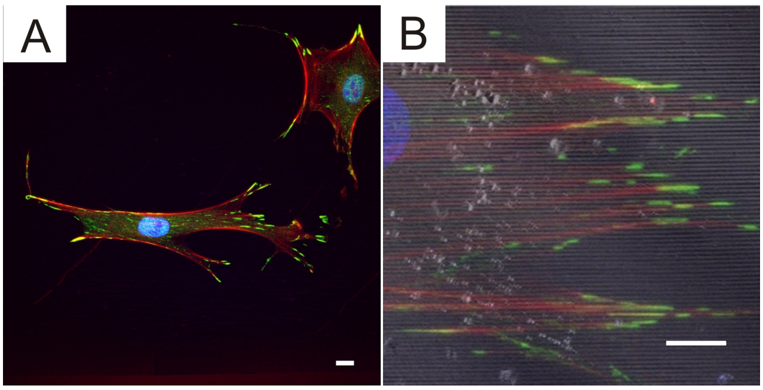

Figure 1: Immunofluorescence micrographs of osteoblast-like cells cultured on nanogrooved polystyrene substrates. Cells tend to expose elongated morphology along the ridges of nanostructure (oriented like scale bar) ; A) Focal adhesions (α-vinculin, green) structure with pitch of 300 nm; B) An overlay of a fluorescent micrograph with a light micrograph. α -Vinculin staining on a pitch of 600 nm (158 nm depth) shows that focal adhesions mainly reside on top of the ridges. Green, vinculin; red, F-actin; blue, nuclei. Bars: 10 µm. [Figure and caption republished by permission of the author, Biomaterials 31 (2010) 3307–3316]

EXPERIMENTAL

To obtain silicon stamps for NIL, first, LIL was performed. A trilayer resist stack, consisting of a bottom antireflective coating (BARC, DUV 30, Brewer Science) of 30 nm thickness, negative tone DUV resist of 120 nm thickness (MA-N 2403, Microresist Technology), and a top antireflective coating (TARC, Aquatar, AZ electronics) of less than 10 nm thickness, was spin-coated subsequently on a polished 4″ silicon wafer of prime quality (Okmetic). LIL exposure was performed in a Lloyd's mirror interference setup with a laser wavelength of 266 nm described in detail previously by us [6]. Exposures for all three pitches are realized with a dose of 4 µJ/cm^2. All latent resist patterns are subsequently developed by immersion for 35 s in OPD 4262 developer (Fujifilm) diluted with water to 75%.

A parallel plate RIE step was conducted for BARC etch-through and tuning of the lateral dimensions of the stamp pattern utilizing a PlasmaTherm 790 equipment (Unaxis) at 15°C. Alternating Cryogenic Inductively-Coupled Plasma Reactive Ion Etching (CryoICP-RIE) is used to tune the nanostructure height. This step was performed in an Adixen AMS100SE ICP-RIE equipment (Alcatel). We used passivation in C_4F_8; etching in SF_6 at 6.3 W/cm^2 ICP source power density with 50 sccm SF_6 during 3 sec etching and 40 sccm C_4F_8 during 2 sec passivation. A liquid nitrogen cooled substrate holder with He backflow of 15 sccm was used for temperature control of the substrate. The nanostructure was smoothened by parallel plate RIE (Unaxis). Both of parallel plate etch steps were performed at a power of 0.6 W/cm^2 with a graphite electrode and a gas flow of 3 sccm O_2; 30 sccm SF_6 at 4 Pa chamber pressure. Etch times varied per pitch and type of etch: BARC etch-through and width tuning for 16 s, 13 s, and 10s; CryoICP-RIE for 45 s, 36 s, and 22 s; and smoothening for 60 s, 40 s, 22 s for the pitch sizes of 1000 nm, 600 nm, and 300 nm, respectively in all steps.

NIL was carried out on medical grade titanium of 100 mm diameter and a thickness of 0.8 mm (Bimo Metals). These wafers were lapped by the supplier and further polished in-house to a roughness of R_a=0.7 nm using Chemical Mechanical Polishing (CMP). A SemiSperse 25 slurry diluted 3:1 with water and Mecapol E460 equipment (Presi) and a IC1000 polishing pad (Rohm and Haas) were used for CMP. After polishing, the wafers were cleaned in DI water and dried at 60°C. A thermomouldable MR-I 8020 resist (Microresist) was spin-coated onto the wafers. The resist speeds per pitch were selected by the spin-curve provided by the supplier at 1500 rpm, 2000 rpm, and 3000 rpm for 1000 nm, 600 nm, and 300 nm pitches, respectively. NIL was performed using an Eitre 6 machine (Obducat) at a temperature 160°C, a pressure of 40 bars and an imprint time of 120 s.

After nanoimprinting, the NIL masking layers were used for final pattern transfer by RIE in chlorinated inductively coupled plasma using Cl_2 33 sccm (37%); CF_4 2.3 sccm (2.5%); Ar 50 sccm (58.3%); O_2 2 sccm (2.2%). A ICP power of 15.3 W/cm^2 and an RF power of 0.76 W/cm^2 were selected. Operating pressure was 3 Pa and the substrate holder temperature was 40°C. RIE was conducted in an Oxford 100 ICP 180 dry etching equipment (Oxford Instruments). The etch times used were: 65 s, 47 s, and 35 s for a pitch of 1000 nm, 600 nm, and 300 nm, respectively.

Titanium discs of 5 mm diameter were cut with electric discharge machining (EDM) and cleaned in series of organic solvents (chloroform, toluene, isopropanol; Sigma Aldrich) and finally boiled 2 times for 10 minutes in miliQ water.

RESULTS AND DISCUSSION

We developed a novel approach to produce nanopatterned implants by combining NIL and chlorine based ICP-RIE process. We investigated the various individual lithographic process steps to provide a nanofabrication scheme that delivers systematic control of the nanostructure dimensions starting with optimization of the silicon stamps for NIL. Based on the reference material generated in previous studies using polystyrene [3], here, we aimed for the same ridge width (R) to groove width (G) to height (H) ratio of 1: 1: 1 at three different pitches: 300, 600 and 1000 nm in implant-compatible titanium. LIL-fabricated stamps yield large areas of up to 5 cm^2. Unfortunately, LIL as a primary pattern technique is highly sensitive to changes in the wafer quality and its reflectivity, therefore, we prefered NIL to transfer the nanostructure pattern onto the titanium wafers. Subsequently, ICP-RIE was used to transfer a uniform nanograting produced in the NIL resist into the titanium. To provide suitable implants for biological studies in rabbits 5 mm diameter discs were cut from the highly uniformly patterned area of the 4″ titanium wafers.

Firstly, LIL exposure and development of the trilayer negative DUV resist had to be performed separately for the three different pitches. The resulting line width in the LIL resist yields a ratio of ridge width-to-groove width just above 1. To yield a ridge width-to-groove width ratio of 1 in the titanium nanostructure, the stamp dimensions had to be optimized. A short, etch time controlled, parallel plate etch to break through the BARC layer of the LIL resist and to achieve the desired stamp grove width was performed. Subsequently, an alternating CryoICP-RIE fluorine plasma was used to achieve the required height of the nanostructure in the silicon stamp, which is also controlled by the etch time. During pattern transfer in titanium, the etch resistivity of the NIL resist in chlorine plasma is relatively poor. Therefore, a nanostructure in the stamp is fabricated with an aspect ratio of 1.6, 2.4 and 2.5, for the three pitches 1000nm, 600nm, and 300nm, respectively, which allows us to transfer the pattern into a NIL resist layer of sufficient thickness. Initial imprint experiments showed that the sidewalls were too rough and lifted-off the NIL resist from the titanium. Therefore, we smoothened the silicon stamps by a parallel plate RIE post-etch, which also results in a slight taper of approximately 4º (estimated from the scanning electron micrographs). Figure 2 depicts the final results for the 300 nm pitch nanograting after each of the steps as one representative example of the stamp nanofabrication process.

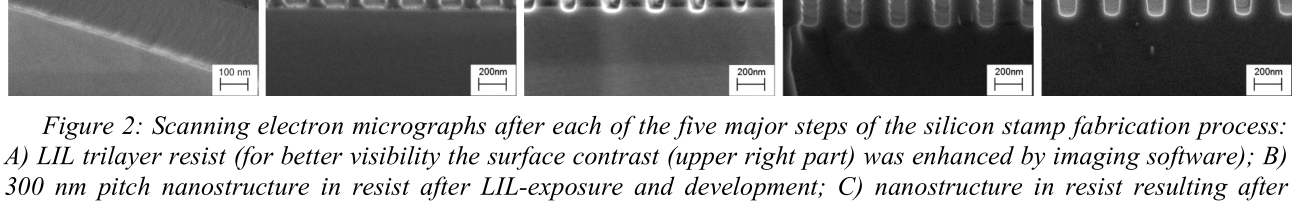

Figure 2: Scanning electron micrographs after each of the five major steps of the silicon stamp fabrication process: A) LIL trilayer resist (for better visibility the surface contrast (upper right part) was enhanced by imaging software); B) 300 nm pitch nanostructure in resist after LIL-exposure and development; C) nanostructure in resist resulting after pattern transfer etch into BARC; D) resulting nanostructure after CryoICP-RIE; E) smoothened nanostructure after parallel plate RIE.

NIL was performed for all three pitches according to the process parameter described in the experimental section. Carrying out the pattern transfer into titanium in an Oxford 100 etcher by inductively coupled chlorine plasma, the low etch selectivity between titanium and polymer nanoimprint mask in the chlorine etch step must be compensated by imprinting into a relatively thick resist. Although NIL-fabricated nanostructures well below the feature size of 25 nm were reported [4], the quality of the titanium wafers and the low etch selectivity restricted us in this study to nanogratings with 300 nm pitch as the smallest realized nanostructure in medical grade titanium. We hypothesize that the titanium oxide layer, which is natively formed on the titanium surface, is difficult to etch and is mainly removed by the physical ion bombardment during the chlorine etch. Literature reports an etch rates for titanium oxides being 20 to 40 times lower than for titanium [5]. Such estimate suggests that during the first approximately 20 s of etching only the oxide is removed, but a significant part of the resist will be lost, too, limiting the fabrication of even smaller dimensions. Finally, successful results of the pattern transfer into titanium for the three pitch sizes are shown in Figure 4A-C, respectively. The final dimensions of the structures are summarized in Table 1.

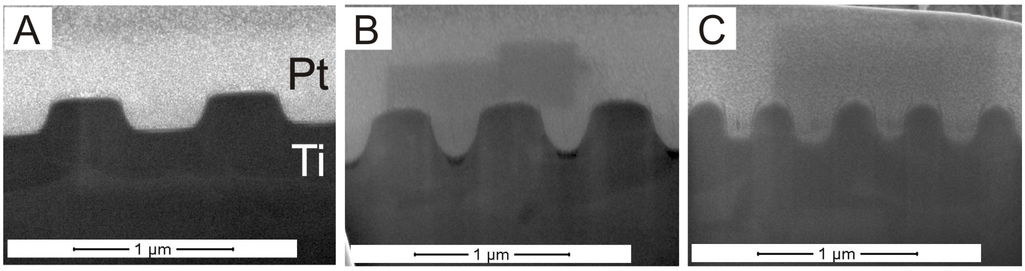

Figure 4: Scanning electron micrographs of nanostructures in titanium resulting after NIL and RIE pattern transfer. (Cross sections made by Focused Ion Beam milling using Pt as a protective layer): A) 1000 nm pitch B) 600 nm pitch and C) 300 nm pitch

Table 1. Dimensions realized in the silicon stamp and titanium structures created using this stamp.

Pitch size (P) [nm]	**Stamp dimensions[nm]**	**Titanium dimensions [nm]**
1000	R 550 ± 40; G 470 ± 48; H 760 ± 18	R 460 ± 10 nm; G 530 ± 11 nm; H 332 nm
600	R 307 ± 18; G 292 ± 13; H 700 ± 20	R 312 ± 16 nm; G 285 ± 11 nm; H 205 nm
300	R 177 ± 6; G 148 ± 11; H 368 ± 17	R 156 ± 10 nm; G 140 ± 9 nm: H 193 nm

CONCLUSION

We developed a large-area nanofabrication route by a combination of NIL and chlorine ICP-RIE ready to obtain highly regular, scalable nanostructures in medical grade titanium wafers and provided 5mm diameter discs thereof, for subsequent implantation studies. Utilizing this novel process systematic modification of the pattern dimensions can be realized. Silicon NIL stamps were produced by LIL and a three step RIE process consisting of BARC break-through, alternating fluorine CryoICP-RIE and RIE smoothening. Stamps with three different pitches (1000 nm, 600 nm and 300 nm) were used for thermal nanoimprint onto the surfaces of polished titanium wafers. Subsequently, pattern transfer to the titanium took place in chlorine ICP-RIE realizing features with R:G:H ratios close to the requirements of 1:1:1.

ACKNOWLEDGEMENTS

This project is sponsored by the Dutch Technology Foundation (STW NTH.7621)

REFERENCES

1. Lord, M.S., M. Foss, and F. Besenbacher, *Influence of nanoscale surface topography on protein adsorption and cellular response.* Nano Today, 2010. **5**(1): p. 66-78.
2. Nel, A.E., et al., *Understanding biophysicochemical interactions at the nano-bio interface.* Nat Mater, 2009. **8**(7): p. 543-557.
3. Lamers, E., et al., *The influence of nanoscale grooved substrates on osteoblast behavior and extracellular matrix deposition.* Biomaterials, 2010. **31**(12): p. 3307-3316.
4. Chou, S.Y., P.R. Krauss, and P.J. Renstrom, *Imprint lithography with 25-nanometer resolution.* Science, 1996. **272**(5258): p. 85-87.
5. Parker, E.R., et al., *Inductively Coupled Plasma Etching of Bulk Titanium for MEMS Applications.* Journal of The Electrochemical Society, 2005. **152**(10): p. C675-C683.
6. Luttge, R et al., *Laser interferometric nanolithography using a new positive chemical amplified resist.* Journal of Vacuum Science and Technology B: Microelectronics and Nanometer Structures 25 (6), pp. 2476-2480

CONTACT

* R. Luttge, tel:+31 53 4892742; r.luttge@utwente.nl