Metal mesh electrode array fabricated by plate-to-roll nanoimprint lithography

Kai Xu¹ · Muyi Yang¹ · Yong Zhou¹ · Liang Wang¹

Received: 10 June 2019 / Accepted: 3 January 2020 / Published online: 7 January 2020
© Springer Nature Switzerland AG 2020

Abstract

Nanoimprint lithography has long been considered a way of fabricating micronano structures in a high-efficiency manner. Based on this method, various 2D and 3D structures with feature sizes ranging from a few micrometers down to a single nanometer have been demonstrated. Here, we present the mechanical and control system design of recently developed plate-to-roll nanoimprint equipment. To improve the parallelism between the template and the substrate, we propose a three voice coil motor actuated mechanical structure and improved proportion integration differentiation algorithm, which can provide fast response and precise positioning. We used a template with a grooved structure to test the embossing performance. By using the nanoimprint system, an electrode array based on a metal mesh transparent conductive material was fabricated on a flexible substrate, which shows the great potential of this system for the fabrication of flexible devices.

Keywords Nanoimprint · Voice coil motor (VCM) · Proportion integration differentiation (PID) · Flexible devices

1 Introduction

Micronano fabrication is regarded as one of the most advanced technologies together with artificial intelligence technology and biotechnology in the twenty-first century. Currently, different kinds of micronano fabrication techniques, such as electron beam lithography [1], photolithography and focused ion beam lithography [2], have been well developed and have shown their abilities in the manufacturing of semiconductors and flexible electronics [3]. However, the working principles of all these techniques are complicated, and the fabrication of corresponding equipment can also be very costly [4]. To fabricate micronano structures in a high-efficiency manner, nanoimprint lithography (NIL) [5–7] was introduced as a simple, low-cost, and high-throughput method. Since the NIL process is based on direct mechanical deformation, the resolution of nanostructures is not limited to light diffraction or beam

scattering, which are common in conventional nanolithography techniques. Due to its great potential in large format micronano pattern fabrication, NIL has been widely researched and has already been developed from plate-type NIL [8] to roller-type NIL [9, 10] to meet the need for novel applications in manufacturing flexible transparent conductive materials as a substitute for traditional indium tin oxide (ITO), which is vital in flexible electronics such as flexible display panels [11, 12], flexible solar cells [13–15] and flexible sensors [16–18].

Despite the advantages, there are several challenges to realizing high quality imprinting since the mechanical imprinting process is always followed by potential possibilities of causing defects [19–21]. The parallelism between the substrate and the template, the deformation of the substrate causing the cured UV-resist during the imprinting process, and the small vibration when the template is brought into contact with the substrate can all have

✉ Liang Wang, lwang121@ustc.edu.cn | ¹Anhui Key Laboratory of Optoelectronic Science and Technology, Department of Optics and Optical Engineering, University of Science and Technology of China, No. 96, JinZhai Road Baohe District, Hefei 230026, Anhui, China.

serious impacts on the imprinting results. Therefore, the mechanical design and control system are of great importance for providing a stable imprinting condition.

In this study, we demonstrated a mechanical and control system that can be used in recently developed plate-to-roll nanoimprint lithography (P2RNIL) [22] equipment. To realize precise control of the template, a delicate mechanism actuated by three fast-response voice coil motors (VCMs) was designed. A flexure structure was integrated into the mechanism to give passive adjustment when the template is not parallel enough with the substrate, which is an inevitable situation as a result of the limited accuracy the control system can provide. A spray nozzle was used to achieve uniform coating and efficient usage of UV curable resist. The spraying speed and resist amount can be adjusted together with the motion of the flexible substrate. After this work, we designed a template with intersecting grooves and applied NIL on a flexible substrate through our system. The whole system was then used to fabricate a double-layer transparent conductive rhombic electrode array based on a metal mesh to show its great potential in fabricating flexible transparent conductive materials.

2 Methods

2.1 Mechanical structure and working procedure

A schematic diagram of the P2RNIL system is shown in Fig. 1. The imprinting process starts with the spray coating of UV curable resist and the delivery of the flexible substrate. When the target area is moved underneath the template, the wind up roller stops rotating while providing a torque of a certain size to keep the tension of the substrate

Fig. 1 A schematic of the P2RNIL process

constant, which can be sensed by a strain sensor. Then, three VCMs are controlled separately to bring the template into full contact with the substrate and maintain the parallelism at the same time. By carrying out UV exposure right through the transparent template, the UV curable resist is cured and forms a complementary pattern defined on the template by e-beam nanolithography methods. The template is lifted up immediately when the exposure is done. The cured resist is separated from the template and stays on the substrate because there exists an anti-stick layer on the surface of the template. Then, the rollers start to rotate and proceed into the next turn.

The imprinting mechanism plays an important role in the P2RNIL system. The movement of the template can be controlled precisely by three VCMs, whose positions are recorded by three high-precision grating rulers. As shown in Fig. 2, the template can be fixed on a vacuum chunk that is connected to the imprinting mechanism through a flexure part. As a result, the imprinting template can be fabricated based on quartz wafers rather than roller-based Ni molds, which are necessary in roller-type NIL but hard to fabricate and maintain. Since the precision of the grating rulers are limited, the template and the substrate are hard to make perfectly parallel. Here, the flexure part can provide tiny adjustments to avoid displacement, which occurs when two unparallel surfaces come into contact.

2.2 Control circuit and methods

As a professional chip for controlling motors, the operation speed of the DSP320F2812 is very considerable. Considering its limited storage space, it needs to expand RAM and Flash to enlarge the storage capacity. The peripheral circuit mainly includes a current detection circuit (feedback information from current sensors), a position detection circuit (feedback information from grating rulers), three independent driver circuits, and high-speed optical coupler circuits. There are 16 PWM signal outputs that can drive multiple motors at the same time.

Fig. 2 A 2D model of the imprinting mechanism

In the servo system of a voice coil motor controlled by PWM, the voice coil motor with a small duty cycle PWM signal has a “dead zone”, which leads to an increase in adjusting time and a deterioration of stability in the control process. This is called the PWM “control dead zone” [23]. Because the voice coil motor itself cannot respond quickly, a conventional PID control algorithm [24–26] cannot meet the performance requirement of fast response. To suppress the defect caused by the “control dead zone”, control algorithms based on speed loop and position loop can be developed to improve the response time. However, the velocity is unstable and difficult to collect, and we can obtain the current flow through the VCM with sensors easily, so we proposed an improved dual closed-loop control strategy [27] based on a current loop and position loop.

A typical traditional PID position controller formula is given by

$$y(t) = k_p e(t) + k_i \int e(t) dt + k_d \frac{de(t)}{dt} \quad (1)$$

The input variable of the PID control algorithm is the deviation signal $e(t)$ of the expected value $r(t)$ and the output value $y(t)$. The PID position controller calculates the output value $y(t)$ according to the deviation signal $e(t)$ and then drives the voice coil motor with the PWM duty cycle corresponding to the output value $y(t)$. In fact, the feedback of the current loop is related to the position deviation, and the ‘I’ (integral) control link of the ‘P’, ‘I’, ‘D’ algorithm in the position loop could be realized based on the current information of the VCM, so we combined the current loop and position loop to control the voice coil motor servo system. The MATLAB simulation model is shown in Fig. 3. The ACR(s) is the transfer function of current regulator, Gpwm(s) is the transfer function of the PWM drive circuit, VCM(s) is the transfer function of VCM,

HALL(s) is the transfer function of the Hall current sensor, and GR(s) is the transfer function of the grating ruler.

The result of the current loop is given by

$$M = ck_p i(t) + ck_i \int i(t) dt \quad (2)$$

where ck_p is the proportional coefficient of the current loop and ck_i is the integral coefficient of the current loop. Thus, the final formula of the PID controller is given by

$$y(t) = K_p e(t) + K_i \int (e(t) + M) dt + K_d \frac{de(t)}{dt} \quad (3)$$

The main features of the improved dual closed-loop VCM position tuning system are that the position and current of a VCM are controlled by two associated regulators. The function of the current loop is to feedback the current flowing through the VCM to the integral part of the position PID control. When the position is less than the given value, the current inner loop will increase the current to the given value, and the effect of position loop integrating will increase the output, so the current of the VCM will increase. The VCM obtains acceleration and continues to move. The adjusting time of the VCM position tuning system will be decreased greatly based on the dual closed-loop control strategy.

2.3 Fabrication of the electrode array

We designed a rhombic electrode double-layer array commonly used in touch detectors, as shown in Fig. 4. The two groups of electrodes, insulated to each other, were distributed in two different layers, forming the electrode structure of a capacitive touch sensor. The electrodes were formed by a metal mesh instead of ITO to obtain flexibility on the basis of transparency and conductivity. The mesh consists of metal wires with a width of 1 μm , a pitch of 35 μm and an angle of 60°.

Figure 5 shows the processing flow. Before the NIL process, the metal mesh was prepared on a quartz wafer by a traditional planar process that contained three steps: First, to make the metal structure easy peel off, an anti-stick treatment was performed on the quartz, in which the quartz was immersed in the solution that was made by dropping 1 μl of FDTS into heptane. Then, an Al film with a thickness of 600 nm was deposited on the wafer by Ebeam deposition. Once the deposition was finished, the pattern, as the mask of dry etch, was produced by photolithography. Then, the metal mesh was fabricated by inductively coupled plasma (ICP) etching (Oxford Instrument ICP180).

This quartz wafer with a metal mesh structure was used as the template for nanoimprint lithography, and a polyethylene terephthalate film (PET film) was used as the

Fig. 3 VCM dual closed-loop PID position tuning system

Fig. 4 **a** The metal mesh structure of the electrodes. **b** Picture of the electrode array

Fig. 5 Processing flow of the electrode array

substrate. The metal mesh was transferred to the PET by the adhesion of UV curing adhesive (PhiChem, KY90F9-19). In the final step, two pieces of PET were bonded back to back by UV curing adhesive to form a double-layer electrode structure and the electrodes.

3 Results

3.1 MATLAB simulation results and analysis

First, we performed the traditional PID algorithm, and the 'P', 'I', 'D' parameters were set up according to the Ziegler–Nichols formula [28, 29] ($P = 3000$, $I = 0.0002$, $D = 50$). The adjusting time is shortened, but the overshoot and oscillation still exist, as shown in Fig. 6. To ensure the stability and quick response of the dual closed-loop PID algorithm, we used a 50-fold algorithm to select the optimal PID control parameters. First, the proportional parameters were adjusted to obtain the response curves with fast response and small overshoot. Then, the integral parameter was set up to reduce the steady-state error. Lastly, the differential parameters were added to improve the

dynamic hysteresis characteristics of the system. Finally, we picked out the parameters of the fitness center of the corresponding area as follows:

$$K_p = 2238, \quad K_i = 0.02, \quad K_d = 20, \quad cK_p = 0.9, \quad cK_i = 2.4.$$

We conducted the simulation in MATLAB with the dual closed-loop PID control algorithm and traditional PID control algorithm, and the results are shown in Fig. 6.

As shown in the diagram, the adjusting time of the dual closed-loop control system is approximately 40 ms, and the position error is $\pm 0.5 \mu\text{m}$. Both the overshoots and oscillation no longer exist, which illustrates that the response speed, accuracy and stability of the dual closed-loop PID control algorithm are better than those of the traditional PID control algorithm and are in full compliance with the design requirements.

3.2 Verification of imprinting performance

To verify the actual imprinting ability of the system, a silicon wafer was used as a master template. By using electron-beam lithography (JEOL 6300FS) and ICP etching, patterns with mutually intersecting grooves with widths of 200 nm and 500 nm were fabricated on the wafer. The nanoimprint experiment was performed on a PET substrate. The results were observed by scanning electron microscopy (SEM) and are shown in Fig. 7. The line width on the PET substrate matches the groove width on the template, which indicates that our nanoimprint system can accurately transfer the strip pattern.

3.3 The properties of the fabricated metal mesh array

The double-layer metal mesh electrode array, which contains 6 rhombic electrode structures, was successfully

Fig. 6 A comparison of the simulation results

Fig. 7 **a–d** Contrast before and after nanoimprinting. **a** The intersection of the 200–200 nm grooves on the template. **b** Imprinting result of the 200–200 nm groove intersections. **c** The intersection

of the 500–200 nm grooves on the template. **d** Imprinting result of the 500–200 nm groove intersections

fabricated on a flexible substrate and can be bent in any direction.

To characterize the performance of the electrode, we measured the change in the resistance between the two ends of each electrode before and after imprinting, as shown in Fig. 8. The change in resistance across the electrode indicates the degree of damage to the electrode pattern during the imprint process. The average rate of change in the resistance values of the six electrodes is approximately 16%, which shows that the damage to the metal structure is small in the imprint process.

As shown in Fig. 8, the optical transmittance of the metal electrode array was tested using a spectrometer (SolidSpec-3700). The transmittance of the entire sample is uniform within a wavelength range from 400 to 800 nm, approximately 73%. Because the electrode array is a combination of metal mesh and PET film, the transmittance of the metal mesh itself can be calculated by dividing the overall transmittance by the transmittance of the two layers of PET. Therefore, the transmittance of a single-layer metal mesh is 94%, which is sufficient for a touch sensor [30].

Fig. 8 The resistance of the 6 electrodes before and after nanoimprint and the transparency of the PET, metal mesh and total sample

3.4 Mechanical test of the metal mesh array

To verify the good mechanical properties and robustness of the fabricated flexible sample, we performed bending test with a large bending radius 20 mm. By setting 1000 bendings as a bending cycle and measuring the resistance of the electrode after each cycle, we aimed to submit the sample to at least 20 cycles unless the metal lines broke at the joint before that.

Figure 9 shows the resistance variation of our test sample. It is clearly found that the resistance fluctuates around 41.5Ω with a small deviation ($\pm 1.5\%$) which is believed to be mainly caused by measurement error. After the bending test, surface morphology of the metal mesh array was characterized by scanning electron microscopy (Hitachi SU8220), which is shown in Fig. 10. No obvious fractures of the metal lines was found during the characterization and it is clearly illustrated that the main part of the metal structures is enclosed and got protected by the cured UV adhesive layer with only a small part of it exposed to the environment.

4 Conclusions

In summary, we designed plate-to-roll nanoimprint equipment with a stable mechanical structure and stable control system and successfully fabricated a double-layer electrode structure. The results demonstrate the potential of our nanoimprint system in the manufacture of flexible metal mesh materials.

Fig. 9 The mechanical bending equipment used for bending test and measured resistance after each bending cycle

Fig. 10 SEM picture of the fabricated metal mesh array after the bending test

Funding This work is supported by the National Key R&D Program of China (Grant No. 2018YFB2200900); National Science Foundation of China Grant No. 61775206. The fabrication work was partially carried out at the USTC Center for Micro and Nanoscale Research and Fabrication.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Vieu C, Carcenac F, Pepin A, Chen Y, Mejias M, Lebib A, Manin-Ferlazzo L, Couraud L, Launois HJ (2000) Electron beam lithography: resolution limits and applications. *Appl Surf Sci* 164(1–4):111–117
2. Volkert CA, Minor AM (2007) Focused ion beam microscopy and micromachining. *MRS Bull* 32(5):389–399
3. Nathan A, Ahnood A, Cole MT, Lee S, Suzuki Y, Hiralal P, Bonaccorso F, Hasan T, Garcia-Gancedo L, Dyadyusha A, Haque S, Andrew P, Hofmann S, Moultrie J, Chu DP, Flewitt AJ, Ferrari AC, Kelly MJ, Robertson J, Amaratunga GAJ, Milne WI (2012) Flexible electronics: the next ubiquitous platform. *Proc IEEE* 100:1486–1517. <https://doi.org/10.1109/Jproc.2012.2190168>
4. Altissimo M (2010) E-beam lithography for micro-/nanofabrication. *Biomicrofluidics* 4(2):026503. <https://doi.org/10.1063/1.3437589>
5. Guo LJ (2007) Nanoimprint lithography: methods and material requirements. *Adv Mater* 19(4):495–513
6. Schift H (2008) Nanoimprint lithography: an old story in modern times? A review. *J Vac Sci Technol B* 26(2):458–480. <https://doi.org/10.1116/1.2890972>
7. Schift H (2015) Nanoimprint lithography: 2D or not 2D? A review. *Appl Phys A Mater* 121(2):415–435. <https://doi.org/10.1007/s00339-015-9106-3>
8. Chou SY, Krauss PR, Renstrom PJ (1996) Nanoimprint lithography. *J Vac Sci Technol B Microelectron Nanometer Struct Process Meas Phenom* 14(6):4129–4133
9. Kooy N, Mohamed K, Pin LT, Guan OS (2014) A review of roll-to-roll nanoimprint lithography. *Nanoscale Res Lett* 9(1):320
10. Ahn SH, Guo LJ (2008) High-speed roll-to-roll nanoimprint lithography on flexible plastic substrates. *Adv Mater* 20(11):2044–2049. <https://doi.org/10.1002/adma.200702650>
11. Sierros KA, Morris NJ, Kukureka SN, Cairns DR (2009) Dry and wet sliding wear of ITO-coated PET components used in flexible optoelectronic applications. *Wear* 267(1–4):625–631. <https://doi.org/10.1016/j.wear.2008.12.042>
12. Ding XW, Yan JL, Li T, Zhang LY (2012) Transparent conductive ITO/Cu/ITO films prepared on flexible substrates at room temperature. *Appl Surf Sci* 258(7):3082–3085. <https://doi.org/10.1016/j.apsusc.2011.11.041>
13. Kim M-S, Kim J-S, Cho JC, Shtein M, Kim J, Guo LJ, Kim JJ (2007) Flexible conjugated polymer photovoltaic cells with controlled heterojunctions fabricated using nanoimprint lithography. *Appl Phys Lett* 90(12):123113
14. Na SI, Kim SS, Jo J, Kim DY (2008) Efficient and flexible ITO-free organic solar cells using highly conductive polymer anodes. *Adv Mater* 20(21):4061–4067. <https://doi.org/10.1002/adma.200800338>
15. Sibinski M, Znajdek K, Walczak S, Sloma M, Gorski M, Cenian A (2012) Comparison of ZnO: Al, ITO and carbon nanotube transparent conductive layers in flexible solar cells applications. *Mater Sci Eng B Adv* 177(15):1292–1298. <https://doi.org/10.1016/j.mseb.2012.03.037>
16. Khan S, Lorenzelli L, Dahiya RS (2015) Technologies for printing sensors and electronics over large flexible substrates: a review. *IEEE Sens J* 15(6):3164–3185
17. Roberts ME, Mannsfeld SCB, Stoltenberg RM, Bao ZN (2009) Flexible, plastic transistor-based chemical sensors. *Organ Electron* 10(3):377–383. <https://doi.org/10.1016/j.orgel.2008.12.001>
18. Smith JT, Shah SS, Goryll M, Stowell JR, Allee DR (2014) Flexible ISFET biosensor using IGZO metal oxide TFTs and an ITO sensing layer. *IEEE Sens J* 14(4):937–938. <https://doi.org/10.1109/Jsen.2013.2295057>
19. Hirai Y, Yoshida S, Takagi N (2003) Defect analysis in thermal nanoimprint lithography. *J Vac Sci Technol B* 21(6):2765–2770. <https://doi.org/10.1116/1.1629289>
20. Hiroshima H, Komuro M (2007) Control of bubble defects in UV nanoimprint. *Jpn J Appl Phys* 46(9b):6391–6394. <https://doi.org/10.1143/jjap.46.6391>
21. Higashiki T, Nakasugi T, Yoneda I (2011) Nanoimprint lithography for semiconductor devices and future patterning innovation. In: *Proceeding of SPIE 7970, Alternative lithographic technologies III*, 797003. <https://doi.org/10.1117/12.882940>
22. Xu K, Luo H, Qin J, Yang M, Guo S, Wang LJ (2018) Flexible devices fabricated by a plate-to-roll nanoimprint lithography system. *Nanotechnology* 30(7):075301
23. Wang JH, Yin HR, Zhang JL, Li HD (2006) Study on power decoupling control of three phase voltage source PWM rectifiers. In: *2006 CES/IEEE 5th international power electronics and motion control conference*, p 401
24. Ang KH, Chong G, Li Y (2005) PID control system analysis, design, and technology. *IEEE Trans Control Syst Technol* 13(4):559–576. <https://doi.org/10.1109/Tcst.2005.847331>
25. Astrom KJ, Hang CC, Persson P, Ho WK (1992) Towards intelligent PID control. *Automatica* 28(1):1–9
26. Li Y, Ang KH, Chong CCY (2006) PID control system analysis and design: problems, remedies, and future directions. *IEEE Control Syst Mag* 26(1):32–41

27. Xu SG, Wang JP, Xu JP (2013) A current decoupling parallel control strategy of single-phase inverter with voltage and current dual closed-loop feedback. *IEEE Trans Ind Electron* 60(4):1306–1313. <https://doi.org/10.1109/Tie.2011.2161660>
28. Hang CC, Astrom KJ, Ho WK (1991) Refinements of the Ziegler–Nichols tuning formula. *IEEE Proc D* 138(2):111–118. <https://doi.org/10.1049/ip-d.1991.0015>
29. Hagglund T, Astrom KJ (2004) Revisiting the Ziegler–Nichols tuning rules for PI control: part II. The frequency response method. *Asian J Control* 6(4):469–482
30. Chan SH, Li MC, Wei HS, Chen SH, Kuo CC (2015) The effect of annealing on nanothick indium tin oxide transparent conductive films for touch sensors. *J Nanomater* 2015:179804. <https://doi.org/10.1155/2015/179804>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.