Electronic Supplementary Material (ESI) for Nanoscale.

Electronic Supplementary Information (ESI) for:

Grating-structured metallic microsprings

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1. The rolling results of rectangular nanomembranes with the long side approximately perpendicular to the gratings on the imprinted area.

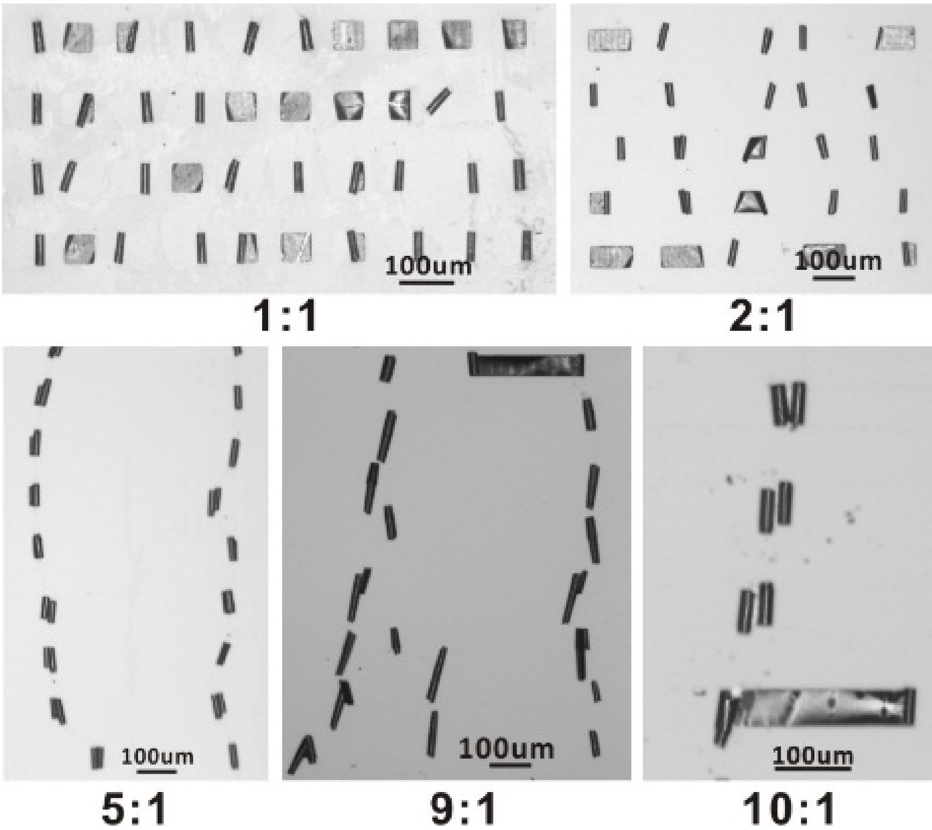

Fig. S1 Optical images of microtubes rolled from arrays of strips with an increasing length to width aspect ratio. All the samples except some defects (unrolled rectangles or displacement caused by incomplete adhesion to substrate) exhibit the same rolling direction, *i.e.* the preferential rolling direction perpendicular to the gratings.

2. Geometry parameters of the grating-structured metallic microsprings used to verify the preferential rolling direction.

Table S1. Geometry parameters (diameter (D_0), pitch (p_0), and misaligned angle (β)) used to calculated the helical angle (α) of grating-structured microspring.

Diameter D_0 (μm)	Pitch p_0 (μm)	Misaligned angle β (deg)	Helical angle α (deg)
17.3		0	90
14.1	125.0	17	70.4
16.2	129.8	20	68.6
15.5	69.1	35	55.9
14.4	51.7	40	48.8
14.0	33.8	52	37.5
15.0	25.2	60	28.1
15.1	15.9	72	18.5
16.6		90	0

3. Imprinted samples for the study of the dependence of microspring diameter on the grating period.

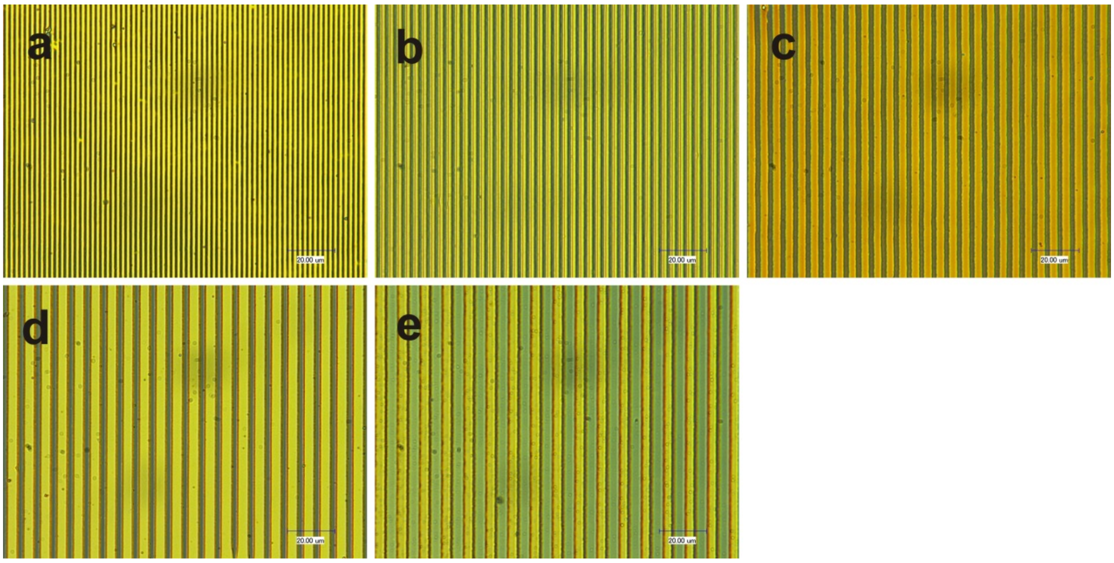

Fig. S2 Optical images of imprinted samples with a grating period of: (a) $\sim 2.3\ \mu m$, (b) $\sim 3.4\ \mu m$, (c) $\sim 5.0\ \mu m$, (d) $\sim 6.7\ \mu m$, and (e) $\sim 9.0\ \mu m$. All the images were obtained at 2000X magnification and the scale bar is $20\ \mu m$.

4. Imprinted samples with a period of $\sim 1.4\ \mu m$ applied for the fabrication of flowing rate sensor.

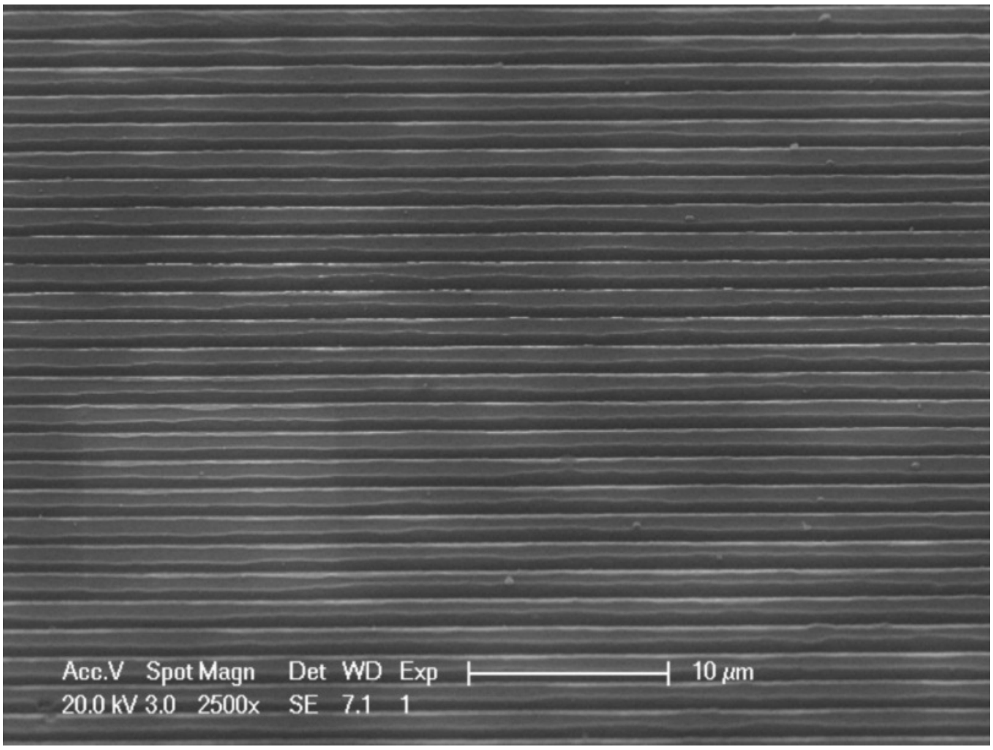

Fig. S3 SEM image of imprinted grating structures with a period of $\sim 1.4\ \mu m$ and the amplitude was estimated as $\sim 100\ nm$.

5. **Geometry parameters of $SP1$, $SP2$, $SP3$, $SP4$ that serves as examples to detect the flowing rate.**

Table S2. Initial parameters of the grating-structured metallic microsprings as flowing rate sensors.

Microsprings	m	D_0 (μm)	p_0 (μm)	t **(nm)**
SP1	2.0	19.8	56.6	70
SP2	2.7	16.3	61.4	40
SP3	4.0	12.9	37.0	30
SP4	5.5	15.8	44.4	40

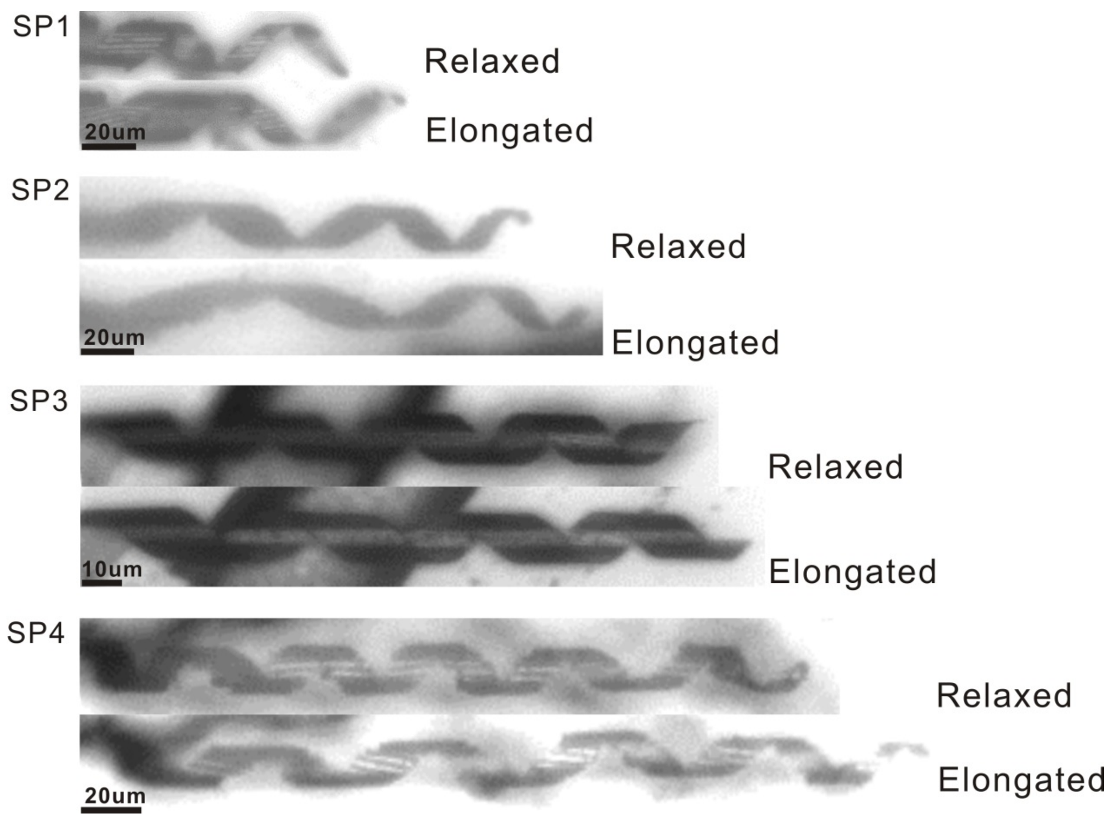

Fig. S4 Corresponding optical images of $SP1$, $SP2$, $SP3$, $SP4$ at the relaxed state and elongated state.

6. Calculations

(1) The surface area of grating-structured metallic microspring

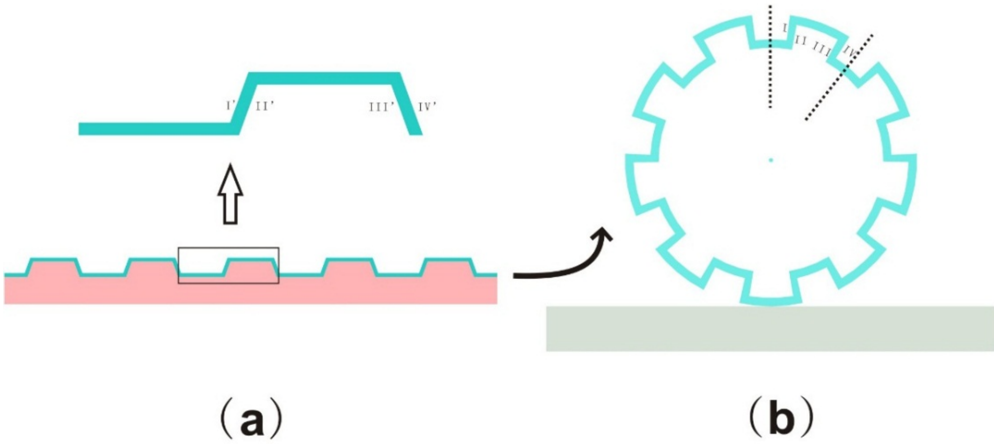

Fig. S5 (a) Schematic diagram of the tapered profile of the gratings and the periodical S-shaped cross-section of the metal nanomembranes deposited on the sacrificial layer. (b) The projection of the cross-section of the grating-structured microsprings.

In Fig. S5(a), we define the facet inclined to the initial substrate as the slope facet and the facet parallel to the substrate as the parallel facet. It's clear that four slope facets (marked by I′, II′, III′, IV′ in (a) and I, II, III, IV in (b)) were added at each period of the grating in comparison to the smooth microspring. For each period, the ratio α_0 of the additional slope facets area to the parallel facets area can be expressed as:

$$\alpha_0 = \frac{4hl}{\lambda l} = \frac{4h}{\lambda} \tag{S1}$$

where h, l, and λ are the amplitude, the length, and the period of the grating, respectively. Then the total ratio α for a grating-structured microspring with a radius R can be written as follows:

$$\alpha = \frac{8\pi Rh}{\lambda^2} \tag{S2}$$

Since the total area of the parallel facets are equal to the one of the smooth microspring S_{smooth}, the total surface area of the grating-structured microspring $S_{structured}$ can be given as:

$$S_{structured} = S_{smooth}(1+\alpha) \tag{S3}$$

(2) The spring constant K of grating-structured metallic microspring

According to the classical elasticity theory, the spring constant k_0 for one turn of the symmetric microspring is expressed by:[1]

$$\frac{1}{k_0}=\frac{4\pi^2}{Gl_0}\left[\frac{p^2}{8\pi^2(1+\upsilon)A}+\frac{(7+6\upsilon)R^2}{(6+6\upsilon)A}+\frac{p^2R^2}{8\pi^2(1+\upsilon)I}+\frac{R^4}{I_p}\right] \tag{S4}$$

where υ and G are the Poisson's ratio and the shear modulus, respectively; l_0, A, I, and I_p are the length, the cross section area, the moment of inertia, and the polar moment of inertial of the initial nanomembrane before rolling into the grating-structured microspring. It's noteworthy that the profile of the imprinted grating structures, for theoretical purpose, can be simplified as 'step' shape resulting in an S-shaped cross section of the replicated metal film. The duty circle (*i.e.* the ratio of the line width to the grating period) of the grating structure in the as-fabricated template applied in this flow rate sensor system is nearly $1{:}2$ (see Fig. S4), which is approximated as $1{:}2$ in our assumption. For the metal nanomembrane with a misaligned angle of β (see the inset of Fig. 3b), given that the number of gratings n on the cross section, is expressed as:

$$n=\frac{w\cos\beta}{\lambda} \tag{S5}$$

and we thus obtain:

$$A=\frac{w\cos\beta}{\lambda}(\lambda+2h)t,$$

$$I=w\cos\beta\cdot\left[\left(\frac{1}{12}+\frac{h}{2\lambda}-\frac{h^2}{\lambda^2}\right)t^3+\left(\frac{h^2}{4}+\frac{h^3}{6\lambda}\right)t\right],$$

$$I_p=w\cos\beta\cdot\left[\left(\frac{1}{12}+\frac{11h}{12\lambda}-\frac{h^2}{\lambda^2}\right)t^3+\frac{ht^2}{2}+\left(\frac{5\lambda^2}{96}+\frac{\lambda h}{4}+\frac{h^2}{8}+\frac{h^3}{6\lambda}\right)t\right]+\frac{\frac{w\cos\beta}{\lambda}\left(\frac{w\cos\beta}{\lambda}-1\right)\left(\frac{2w\cos\beta}{\lambda}-1\right)(\lambda+2h)\lambda^2t}{6}$$

Since t is two orders of magnitude smaller than λ and $I_p \gg I$, eqn (S4) can be further simplified as:

$$\frac{1}{k_0}=\frac{4\pi^2}{Gl_0}\cdot\frac{p^2R^2}{8\pi^2(1+\upsilon)I}=\frac{p^2R^2}{2Gl_0(1+\upsilon)I}=\frac{6p^2R^2}{Gl_0(1+\upsilon)\left[\left(1+\frac{6h}{\lambda}-\frac{12h^2}{\lambda^2}\right)t^3+\left(3h^2+\frac{2h^3}{\lambda}\right)t\right]w\cos\beta} \tag{S6}$$

Hence, the spring constant K of the grating-structured microspring with m turns can be expressed by:

$$\frac{1}{K}=\frac{6mp^2R^2}{Gl_0(1+\upsilon)\left[\left(1+\frac{6h}{\lambda}-\frac{12h^2}{\lambda^2}\right)t^3+\left(3h^2+\frac{2h^3}{\lambda}\right)t\right]w\cos\beta} \tag{S7}$$

(3) Flowing rate (V) as a function of elongation (x)

According the definition of Hookes' law $F_{d-structued} = Kx$, the following expression can be obtained as:

$$\frac{2\mu lw}{\left[\ln\left(\frac{2L}{R}\right)-0.72\right]R}v\cdot\left(1+\frac{8\pi Rh}{\lambda^2}\right)=\frac{Gl_0(1+\upsilon)\left[\left(1+\frac{6h}{\lambda}-\frac{12h^2}{\lambda^2}\right)t^3+(3h^2+\frac{2h^3}{\lambda})t\right]w\cos\beta}{6mp^2R^2}\cdot x \tag{S8}$$

Since $l = m \cdot l_0$, eqn (S8) can be further simplified as:

$$v=\frac{G(1+\upsilon)\left[\left(1+\frac{6h}{\lambda}-\frac{12h^2}{\lambda^2}\right)t^3+(3h^2+\frac{2h^3}{\lambda})t\right]\cos\beta}{12\mu\left(1+\frac{8\pi Rh}{\lambda^2}\right)}\cdot\frac{\left[\ln\left(\frac{2L}{R}\right)-0.72\right]}{m^2p^2R}\cdot x \tag{S9}$$

For the geometric constraint before and after elongating,[2]

$$L = mp_0 + x,$$

$$mp = mp_0 + x,$$

$$4\pi^2R^2 + p^2 = 4\pi^2{R_0}^2 + {p_0}^2,$$

$$\cos\beta = \frac{p_0}{\sqrt{4\pi^2{R_0}^2+{p_0}^2}}$$

By substituting the above relations into eqn (S9), one has:

$$v=\frac{\pi G(1+\upsilon)\left[\left(1+\frac{6h}{\lambda}-\frac{12h^2}{\lambda^2}\right)t^3+(3h^2+\frac{2h^3}{\lambda})t\right]\frac{p_0}{\sqrt{4\pi^2{R_0}^2+{p_0}^2}}}{6\mu\left(\frac{4h\sqrt{4\pi^2{R_0}^2+{p_0}^2-\left(\frac{mp_0+x}{m}\right)^2}}{\lambda^2}+1\right)}\cdot\frac{\ln\left[\frac{4\pi(mp_0+x)}{\sqrt{4\pi^2{R_0}^2+{p_0}^2-\left(\frac{mp_0+x}{m}\right)^2}}\right]-0.72}{(mp_0+x)^2\sqrt{4\pi^2{R_0}^2+{p_0}^2-\left(\frac{mp_0+x}{m}\right)^2}}\cdot x \tag{S10}$$

7. Dependence of the flow rate sensing properties on the grating amplitude

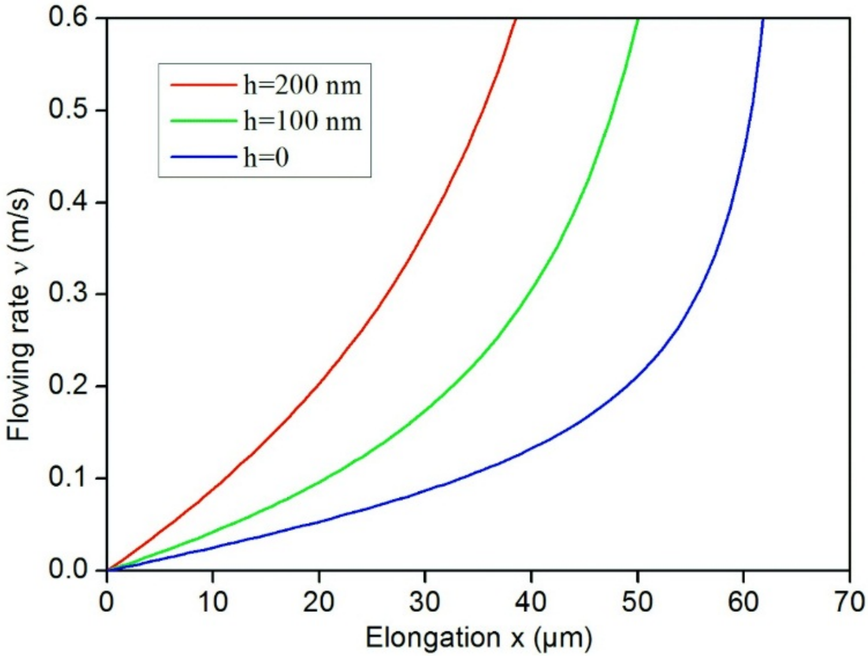

Fig. S6 The flowing rate (v) vs. the elongation (x) for the grating-structured microsprings based on eqn (S10) ($D_0 = 15\ \mu m$, $p_0 = 60\ \mu m$, $m = 4.0$). The solid curves represent microsprings with a grating amplitude of $200\ nm$ (red solid line), $100\ nm$ (green solid line), and 0 (*i.e.* the smooth surface) (blue solid line), respectively.

In order to study the effect of the geometry of the grating structures on the flow rate sensing properties, these well-defined microsprings with a same initial diameter (D_0), pitch (p_0) and turns (m) were analysed by varying the grating amplitude from $200\ nm$ to 0 in a stepwise manner based on eqn (S10). As illustrated in Fig. S6, the microspring was elongated longer with decreasing the grating amplitude at a same flow rate, demonstrating that the elasticity or the sensitivity ($S = \frac{dx}{dv}$)[2] of the grating-structured microspring can be well tailored by the geometry of the gratings.

References

1 P. X. Gao, W. Mai and Z. L. Wang, *Nano Lett.*, 2006, **6**, 2536.

2 W. M. Li, G. S. Huang, J. Wang, Y. Yu, X. J. Wu, X. G. Cui and Y. F. Mei, *Lab Chip*, 2012, **12**, 2322.