Thermal Probe Nanolithography

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Nano / Micro - Manufacturing

Particle Beams    Laser    Mechanical

nm  µm  mm
Overview NanoFrazor

Resolution

- 10 nm HP

Speed

- 500 kHz, 20mm/s

Stitching & Overlay

- 10 nm accuracy

Resists

3D direct-write

~1 nm accuracy in Z

Pattern transfer

- 27 nm hp, LER=1nm
- 60 nm deep in Si

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IBM Research in Rüschlikon

Zurich

- Total: ~300 employees
- ca. 80 researchers in Science & Technology
- mainly basic research in various fields (molecular electronics, spintronics, photonics, microfluidics)
- 4 Nobel prize laureates

thermal probe team at IBM (2011)

Felix Holzner, Armin Knoll, Michel Despont, Philip Paul, Urs Dürig
Scanning Probe Microscopy

1981: Scanning Tunneling Microscope (STM)

Binnig and Rohrer, IBM Rüschlikon, Nobel Price 1986

1986: Atomic Force Microscope (AFM)

First AFM: deflection measured with STM


Today: ~50 companies selling Scanning Probe Microscopes

> 20 different imaging methods
Scanning Probe Lithography (SPL)

STM (Tunneling Microscope)

Local Anodic Oxidation

Dagata 1990

Field-induced Deposition


Nano-Scratching

Dong et al., *Small*, 2010

Dip-Pen Nanolithography

Mirkin et al., *Science* 1999, 283, p661

Main issues of SPL:
- only specific applications
- slow
- tip wear
Patterning Principle: Thermal Desorption Scanning Probe Lithography

Heated tip => local evaporation of resist

**Advantages:**
- versatile
- tip preserving
- compatible to CMOS
- in-situ inspection

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Thermal Cantilevers

Heating of the tip:
- Microheater: 2x2 \( \mu \text{m}^2 \) area with higher electric resistivity (lower dopant concentration in Si) heats up to 1000 \(^\circ\text{C}\)

Thermal sensor for measuring topography in special AFM imaging mode
Actuation mechanism

Force control:
- Voltage between cantilever and substrate
  => electrostatic actuation (~1 µs pull-in time)

Electrostatic force:
\[ F_{el} \sim \Delta U^2 \]

Restoring force:
\[ F_k = \Delta z \cdot k_{spring} \]
\[ k_{spring} \approx 1 \text{ N/m} \]
Closed-Loop Lithography

- Direct feedback ⇒ Automated adaption
- Less critical on environment ⇒ Turnaround in seconds

**E-Beam Lithography:**

- Feedback after hours or days ⇒ Control over everything ⇒ Long turnaround
Resist strategies

Challenges:
• efficient thermally activated process
• stability (etching + imaging)

Molecular glass

Unzip polymer

Polyphthalaldehyde (PPA)


Ito et al., Poly. Eng. & Sc., 1983
Coulembier et al., Macromolecules, 2010
Resolution

10 nm HP

8 nm HP

Limitations:
• tip size
• temperature
• molecular size
Speed

~1 Mpixels
<12s write time
No errors
<1min overall turnaround

< 1 second write time
No influence on neighbouring pixels
Pixel rate: 500 kHz
Scan speed: 20 mm/s

40 nm pixel pitch
125x100 pixels = 5x4 um
4-5 nm deep

Paul et al., Nanotechnology, 23, 385307, (2012)
Speed

Challenges & Limitations:
1.) vertical tip movement
2.) precise positioning at high scan speed
3.) out-of-plane motion at high scan speed
4.) reaction kinetics of thermal decomposition

Actuation above the resonance frequency

Mechanical high-speed setup

Paul et al., Nanotechnology, 22, 275-306, (2011)
Stitching concept

- Surface roughness after spin coating
- Ca. 1 nm in amplitude
- Randomly distributed
→ Unique in each area

Write first field, and read back with a stitching margin
Move with coarse positioning stage
Read at new position
Correlate the two fields =>
Write second field at correct position

Offset determination: ~1 nm

Paul et al., Nanotechnology, 23, 385307, (2012)
Stitching results

10 nm alignment accuracy

Limited by fine piezo stage

10 µm write field
1100 x 1100 pixels
1 µm stitching margin

Vernier dials:
90 nm, 100 nm pitch

Paul et al., Nanotechnology, 23, 385307, (2012)
Overlay

PPA spin-coated on top of Si structure:
⇒ part of topography remains
⇒ detect with AFM mode
⇒ Write Overlay

Rawlings et al., (2013)
3D patterning

grayscale bitmap => different voltages => different forces => different depths


Replica of the Matterhorn

Closed-Loop Lithography => 1nm accuracy

Zientek et al., (2013)

3D Applications I + II

Positioning and placement of nanoparticles

- Shape matching traps written in PPA by tSPL
- Au nanorods trapped using Capillary Assembly
- Au nanorods transferred to substrate by evaporation of the PPA layer

Multi-Level Archival Data storage

\textit{tSPL in PPA:}

3 level logic + 100 nm pitch
\Rightarrow 99 \, \text{Gbit/in}^2

\textit{Etch transfer:}

29 s reactive ion etching
\Rightarrow \text{Indents transferred in SiO}_2
\Rightarrow \text{Data preservation}


Holzner et al., \textit{Appl. Phys. Lett.}, 99, 023110, (2011)

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3D Application III: High Performance Optical Micro-Cavities

Simulation: >100 x improvement

Gaussian structures by tSPL:

Coupling of light and matter

Figure of merit: Q/V, (Q: quality factor of cavity, V: optical mode volume)

High Q/V enables strong coupling of the light-field in the cavity with an optically active material

Applications:
- single photon emitters
- thresholdless lasing

Pattern transfer

20nm PPA
4nm SiO$_2$
50nm HM

Step 1:
N$_2$/O$_2$ RIE thinning

Step 2:
CHF$_3$ RIE into SiO$_2$

Step 3:
O$_2$ RIE into HM8006

Cheong et al., Nano Letters, **13**(9), 4485-4491, (2013)
Pattern Transfer

Line Edge Roughness in HM8006 layer:

$$0.65 \text{ nm}_{\text{rms}} - 0.9 \text{ nm}_{\text{rms}}$$

$$(3\sigma: 1.95 \text{ nm} - 2.7 \text{ nm})$$

Cheong et al., Nano Letters, 13(9), 4485-4491, (2013)
Outlook

- new resists
- new cantilevers + arrays

**EU project SNM**
- Single Nanometer Manufacturing
- 15 partners

**other applications**
- Chemical patterning
- Biological studies
- Material characterization

**IBM Millipede**

**large stroke system**

**Swiss project (CTI)**
- Nanobridge
SwissLitho AG

Founders:
- Dr. Felix Holzner, CEO, physicist
- Dr. Philip Paul, CTO, engineer

Software:
Dr. Nicolae Suditu

Hardware:
Dr. Simon Bonanni

Controller:
Kartik Buddha

Simulation:
Simon Züst

Advisory board
Dr. Peter Vettiger

Incorporation: 2012
6 people, 6 nationalities
Location: Technopark, Zurich

winner ZKB Pionierpreis
Thank you for your attention!

Product launch at MNE
September 2013 in London
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**References**
Tip Endurance

World

#1

3×10^6 written pixels = 40 µm³

Comparison:
V(tip cone) ≈ 0.13 µm³
(factor 300)

#4

#6
Thermal sensing and imaging

Approach of the thermal sensor

AFM read-out