Align the pattern and Exposure

MICROPOSIT S1813 and S1813 J2 PHOTO RESISTS
Figure 4. Interference Curves

UV light Off

Align the pattern

UV light On
E-beam Projection

Bell Lab (1999)
There was a consortium including Applied Materials, Inc. and ASM Lithography Holding N.V.; Lucent Technologies Inc.; Motorola, Semiconductor Products Sector; Samsung Electronics Co., Ltd.; and Texas Instruments Incorporated (TI).
Imprint Lithography with 25-Nanometer Resolution

Stephen Y. Chou; Peter R. Krauss; Preston J. Renstrom


**Fig. 2.** SEM micrograph of a top view of holes 25 nm in diameter with a period of 120 nm, formed by compression molding into a PMMA film.

**Fig. 3.** SEM micrograph of a top view of trenches 100 nm wide with a period of 250 nm, formed by compression molding into a PMMA film.

**Fig. 5.** SEM micrograph of the substrate in Fig. 2, after deposition of metal and a lift-off process. The diameter of the metal dots is 25 nm, the same as that of the original holes created in the PMMA.

**Fig. 6.** SEM micrograph of the substrate in Fig. 3, after deposition of metal and a lift-off process. The metal linewidth is 100 nm, the same as the width of the original PMMA trenches.
Nanoimprint Lithography

Mold
PMMA
Substrate
Imprint
Remove
Mold
RIE
Evaporation
Lift-off
Ultrafast and direct imprint of nanostructures in silicon

Stephen Y. Chou*, Chris Keimer & Jian Gu

NATURE VOL 417 | 20 JUNE 2002 |

a Contact mould and substrate ($t = 0$)

b Excimer laser irradiation ($t > 0$)

c Silicon embossing ($0 < t < 250$ ns)

d Silicon solidification ($t > 250$ ns)

e Mould and substrate separation

f Reflectivity (a.u.)

0 50 100 150 200 250 300 350 400

Time (ns)
Step and Flash Imprint Lithography

Step 1: Orient template and substrate

Step 2: Dispense drops of liquid imprint resist

Step 3: Lower template and fill pattern

Step 4: Polymerize imprint fluid with UV exposure

Step 5: Separate template from substrate
Nanoimprintors

NX-2000, Nanoimprinter, Nanonex

- Resolution: Sub-50 nanometers, imprint template (mold) limited.
- Alignment: < 500 nm, 3σ (X, Y, and Rotation).
- Flexibility: Handles up to 8 inch wafers, including fragile substrates.
- Field size: 25 x 25 mm full active print area, 100 μm street width.
Imprinting Result

[Images of various imprinted structures with labels: Imprinted 20 nm isolated lines, Imprinted 30 nm dense lines, Imprinted sub-40 nm contacts, Imprinted 90 nm dense lines]
Challenges

- Mask Fabrication (1:1)
- Lift-off process
- Resist
- Mask Design
Soft Lithography

<table>
<thead>
<tr>
<th>Definition of patterns</th>
<th>Photolithography</th>
<th>Soft lithography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid photomask</td>
<td>Elastomeric stamp or mold</td>
<td></td>
</tr>
<tr>
<td>(patterned Cr supported on a quartz plate)</td>
<td>(a PDMS block patterned with relief features)</td>
<td></td>
</tr>
<tr>
<td>Materials that can be patterned directly</td>
<td>Photoresists</td>
<td>Photoresists$^a,e$</td>
</tr>
<tr>
<td>(polymers with photosensitive additives)</td>
<td>SAMs on Au and SiO$_2$</td>
<td></td>
</tr>
<tr>
<td>SAMs on Au and SiO$_2$</td>
<td>SAMs on Au, Ag, Cu, GaAs, Al, Pd, and SiO$_2$$^a$</td>
<td></td>
</tr>
<tr>
<td>Unsensitized polymers$^{b-e}$ (epoxy, PU, PMMA, ABS, CA, PS, PE, PVC)</td>
<td>Precursor polymers$^{c,d}$ (to carbons and ceramics)</td>
<td></td>
</tr>
<tr>
<td>Polymer beads$^d$ Conducting polymers$^d$ Colloidal materials$^{a,d}$ Sol-gel materials$^{c,d}$ Organic and inorganic salts$^d$ Biological macromolecules$^d$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Surfaces and structures that can be patterned

| Planar surfaces | Both planar and nonplanar |
| 2-D structures | Both 2-D and 3-D structures |

Current limits to resolution

| $\sim 250$ nm (projection) | $\sim 30$ nm$^{a,b}$, $\sim 60$ nm$^e$, $\sim 1 \mu$m$^d,e$ (laboratory) |
| $\sim 100$ nm (laboratory) | |

Minimum feature size

| $\sim 100$ nm (?) | 10 (?) - 100 nm |

$^{a,e}$Made by (a) $\mu$CP, (b) REM, (c) $\mu$TM, (d) MIMIC, (e) SAMIM. PU: polyurethane; PMMA: poly(methyl methacrylate); ABS: poly(acrylonitrile-butadiene-styrene); CA: cellulose acetate; PS: polystyrene; PE: polyethylene; and PVC: poly(vinyl chloride)
Figure 2 Schematic procedures for μCP of hexadecanethiol (HDT) on the surface of gold: (a) printing on a planar surface with a planar stamp (21), (b) printing on a planar surface over large areas with a rolling stamp (128), and (c) printing on a nonplanar surface with a planar stamp (174).
Micro-contact Printing

Fig 1. The micro-contact printing (µCP) process: An elastomeric stamp is replicated from a master. After inking of the stamp with a suitable ink, it is fixed on a printing machine with help of which it is brought into conformal contact with a substrate. There the ink forms a self-assembled monolayer (SAM) which can be used as a resist in a subsequent wet etching step.

Fig 2. The stamp replication process: A master with a negative of the desired pattern is cast with a prepolymer. After curing the polymer, the elastomeric stamp is peeled off the master and ready for microcontact printing.
Micro-contact Printing

http://mrsec.wisc.edu/Edetc/nanolab/print/text.html
Micro-contact Printing
Self-Assemble Monolayer (SAM)


<table>
<thead>
<tr>
<th>Ligated Substrates</th>
<th>Disks or Bulk Materials</th>
<th>Nanoparticles or Other Nanostructures</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROH: R–Si–Si–OH</td>
<td>26</td>
<td>55</td>
</tr>
<tr>
<td>ROH: R–Si–H</td>
<td>37</td>
<td>55</td>
</tr>
<tr>
<td>RCOO–R–COOH:</td>
<td>58, 39</td>
<td>40</td>
</tr>
<tr>
<td>ROOCR:</td>
<td>43</td>
<td>40, 42</td>
</tr>
<tr>
<td>ROOCR: Si[111]H</td>
<td>44</td>
<td>40</td>
</tr>
<tr>
<td>ROOCR: Si[100]H</td>
<td>44</td>
<td>40</td>
</tr>
<tr>
<td>End-capped ROH</td>
<td>45</td>
<td>45</td>
</tr>
</tbody>
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</tbody>
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- **Self-Assemble Monolayer (SAM)**

- **Organic Interphase**
  - Denaturates, surface properties
  - Presents chemical functional groups

- **Terminal Functional Group**
  - Organic Interphase (1–3 nm)
  - Provides well-defined thickness
  - Acts as a physical barrier
  - Affects electronic conductivity and local optical properties

- **Spacer (Alkane Chain)**

- **Ligand or Head Group**

- **Metal Substrate**

- **Metal-Sulfur Interface**
  - Stabilizes surface atoms
  - Modifies electronic states

S-Au 25-30 Kcal/mole
Si-O 190 kcal/mole
Figure 7. Schematic illustration of some of the intrinsic and extrinsic defects found in SAMs formed on polycrystalline substrates. The dark line at the metal–sulfur interface is a visual guide for the reader and indicates the changing topography of the substrate itself.

(a) Insertion of a functional adsorbate at a defect site in a preformed SAM. (b) Transformation of a SAM with exposed functional groups (circles) by either chemical reaction or adsorption of another material.
Figure 12. (a) Schematic illustration depicting the application of a PDMS stamp containing thiols to a polycrystalline metal film. The primary mechanisms of mass transport from the stamp to the surface are shown. The grayscale gradient approximates the concentration of thiols adsorbed in the stamp itself. (b) Magnified schematic view that illustrates the variety of structural arrangements found in SAMs prepared by μCP when the stamp is wetted with a 1–10 mM solution and applied to the substrate for 1–10 s.

Figure 17. Schematic illustration of the types of defects in SAMs that can influence the rate of electron transfer in two-terminal (or three-terminal) devices. (a) Chemical reaction with the organic component of SAMs during evaporation of metal films. (b) Formation of metallic filaments during evaporation or operation of the device. (c) Deposition of adlayers of metal on the surface of the substrate supporting the SAM. (d) Formation of oxide impurities on the surface. (e) Organic (or organometallic) impurities in the SAM. (f) Thin regions in the SAM resulting from conformational and structural defects. In e and f the dimension normal to the surface that is denoted by the black arrows indicates the approximate shortest distance between the two metal surfaces; note that these distances are less than the nominal thickness of the ordered SAM.
Figure 21. Schematic illustrations of (a) a mixed SAM and (b) a patterned SAM. Both types are used for applications in biology and biochemistry.

Figure 22. Schematic diagram illustrating the effects that large terminal groups have on the packing density and organization of SAMs. (a) Small terminal groups such as −CH₃, −CN, etc., do not distort the secondary organization of the organic layer and have no effect on the sulfur arrangement. (b) Slightly larger groups (like the branched amide shown here) begin to distort the organization of the organic layer, but the strongly favorable energetics of metal–sulfur binding drive a highly dense arrangement of adsorbates. (c) Large terminal groups (peptides, proteins, antibodies) sterically are unable to adopt a secondary organization similar to that for alkanethiols with small terminal groups. The resulting structures probably are more disordered and less dense than those formed with the types of molecules in a and b.
Figure 23. Schematic illustration of the order–disorder transition evidenced by SAMs of alkanethiolsates terminated with triethylene glycol. The EG₃ group loses conformational ordering upon solvation in water.
Control of crystal nucleation by patterned self-assembled monolayers

a

PDMS stamp

b

"Ink" with HS(CH$_2$)$_{15}$X
Ag, Au, or Pd (50 nm) on Cr (2 nm)
Microcontact print HS(CH$_2$)$_{15}$X

X-terminated SAM

Wash with HS(CH$_2$)$_{15}$CH$_3$

CH$_3$-terminated SAM

Expose (upside down) to crystallization solution

PDMS support

Crystals grow on X-terminated regions

CO$_2$H-terminated SAM

Crystals grow on X-terminated region

CO$_2$H-terminated SAM

100 μm

CH$_3$-terminated SAM
a. HS(CH₂)₁₅CO₂H on Au
   Nucleating plane (015)
   \(d = 35 \, \mu m; \, p = 100 \, \mu m\)
   \([Ca^{2+}] = 10 \, mM; \, N = 100\)

b. HS(CH₂)₂₂OH on Au
   Nucleating plane (0104)
   \(d = 50 \, \mu m; \, p = 100 \, \mu m\)
   \([Ca^{2+}] = 10 \, mM; \, N = 100\)

c. HS(CH₂)₁₁SO₃H on Pd
   Nucleating plane (001)
   \(d = 15 \, \mu m; \, p = 30 \, \mu m\)
   \([Ca^{2+}] = 10 \, mM; \, N = 1,000\)

d. HS(CH₂)₁₅CO₂H on Ag
   Nucleating plane (012)
   \(d = 15 \, \mu m; \, p = 100 \, \mu m\)
   \([Ca^{2+}] = 10 \, mM; \, N = 100\)

e. HS(CH₂)₁₅CO₂H (triangles) +
   HS(CH₂)₁₅CH₃ (stars) on Ag
   Nucleating plane (012)
   \(d = 3 \, \mu m; \, p = 10 \, \mu m\)
   \([Ca^{2+}] = 100 \, mM; \, N = 10,000\)
Patterning of organic single crystals

Nature 444, 913-917 (14 December 2006)
Large On-Off Ratios and Negative Differential Resistance in a Molecular Electronic Device

J. Chen,³ M. A. Reed,¹* A. M. Rawlett,² J. M. Tour²*

19 NOVEMBER 1999 VOL 286 SCIENCE

Fig. 1. Schematics of device fabrication. (A) Cross section of a silicon wafer with a nanopore etched through a suspended silicon nitride membrane. (B) Au-SAM-Au junction in the pore area. (C) Blowup of (B) with 16c sandwiched in the junction. (D) Scanning electron micrograph (SEM) of pyramidal Si structure after anisotropic Si etching. [that is, the bottom view of (A)]. (E) SEM of an etched nanopore through the silicon nitride membrane. (F) The active molecular component 1a and its precursors the free thiophene 1b and the thio-protected system 1a.

Fig. 4. Potential mechanism for the NDR effect. As voltage is applied, the molecules in the SAM (A) undergo a one-electron reduction to form the radical anion (B) that provides a conductive state. Further increase of the voltage causes another one-electron reduction to form the dianion insulating state (C). Q is the charge.
FIG. 1. (a) Optical micrograph of the nanoelectrode array. Inset: AFM image of four Au nanoelectrodes with a Pd nanowire lying across. (b) Schematic diagram of the Pd/molecular wires/Au junctions on a Si/SiO₂ substrate.

FIG. 3. Typical $I$-$V$ curves of molecular devices. (a), (b), and (c) correspond to molecules a, b, and c shown in Fig. 2, respectively.

Geometric Control of Cell Life and Death

SCIENCE • VOL 276 • 30 MAY 1997
**Fig. 1.** Effect of cell spreading on apoptosis. (A) Combined phase contrast-fluorescence micrographs of capillary endothelial cells cultured in suspension in the absence or presence of different-sized microbeads or attached to a planar culture dish coated with FN for 24 hours (23). In the highly spread cell on the 25-μm bead, only the flattened 4',6'-diamidino-2-phenylindole (DAPI)--stained nucleus is clearly visible. (B) Apoptosis in cells attached to different-sized beads, in suspension, or attached to a dish. The apoptotic index was quantitated by measuring the percentage of cells exhibiting positive TUNEL staining (black bars) (Boehringer Mannheim), which detects DNA fragmentation; similar results were obtained by analyzing changes in nuclear condensation and fragmentation in cells stained with DAPI at 24 hours (gray bars). Apoptotic indices were determined only within single cells bound to single beads. Error bars indicate SEM. (C) Differential interference-contrast micrographs of cells plated on substrates micropatterned with 10- or 20-μm-diameter circles coated with FN (left), by a microcontact printing method (29) or on a similarly coated unpatterned substrate (right). (D) Apoptotic index of cells attached to different-sized adhesive islands coated with a constant density of FN for 24 hours; similar results were obtained with human and bovine capillary endothelial cells (28). Bars same as in (B).
Fig. 3. Cell-ECM contact area versus cell spreading as a regulator of cell fate. (A) Diagram of substrates used to vary cell shape independently of the cell-ECM contact area. Substrates were patterned with small, closely spaced circular islands (center) so that cell spreading could be promoted as in cells on larger, single round islands, but the ECM contact area would be low as in cells on the small islands. (B) Phase-contrast micrographs of cells spread on single 20- or 50-μm-diameter circles or multiple 5-μm circles patterned as shown in (A). (C) Immunofluorescence micrographs of cells on a micropatterned substrate stained for FN (top) and vinculin (bottom). White outline indicates cell borders; note circular rings of vinculin staining, which coincide precisely with edges of the FN-coated adhesive islands. (D) Plots of projected cell area (black bars) and total ECM contact area (gray bars) per cell (top), growth index (middle), and apoptotic index (bottom) when cells were cultured on single 20-μm circles or on multiple circles 5 or 3 μm in diameter separated by 40, 10, and 6 μm, respectively.
Fig. 4. Role of different integrin ligands in cell shape-regulated apoptosis. Apoptotic indices (percentage positive TUNEL staining) for cells cultured for 24 hours on unpatterned substrates (black bars) or on 20-μm circles (gray bars) coated with FN, type I collagen (Col I), vitronectin (VN), anti-β1, anti-αvβ3, or antibodies to both integrin β1 and integrin αvβ3 (29).

Hexadecanethiol [HS(CH₂)₁₅CH₃] was printed onto gold-coated substrates with a flexible stamp containing a relief of the desired pattern. The substrate was immersed immediately in 2 mM triethylene glycol-terminated alkanethiol [HS(CH₂)₁₁(OCH₂CH₂)₃OH in ethanol], which coated the remaining bare regions of gold. When these substrates were immersed in a solution of FN, vitronectin, or type I collagen (50 μg/ml in phos-
Electrochemical Desorption of Self-Assembled Monolayers Noninvasively Releases Patterned Cells from Geometrical Confinements

Figure 1. BCE cells were allowed to attach to a surface patterned with C_{11}EG_{3} and C_{18}. Application of a cathodic voltage pulse (−1.2 V for 30 s in this case) released the cells from the microislands. The numbers indicate the time elapsed (in minutes) after the voltage pulse.

J. Am. Chem. Soc. 2003, 125, 2366–2367
Directing cell migration with asymmetric micropatterns

Xingyu Jiang*, Derek A. Brzozowicz*, Amy P. Wong*, Matthieu Piall, and George M. Whitesides††

*Department of Chemistry and Chemical Biology, Harvard University, 12 Oxford Street, Cambridge, MA 02138; and †Department of Molecular and Cell Biology, Harvard University, 16 Divinity Avenue, Cambridge, MA 02138

Contributed by George M. Whitesides, December 2, 2004

Fig. 1. A cartoon illustration of the migration of a typical mammalian cell on a flat surface. This teardrop shape is found in many types of cells. (B) Cells confined to squares preferentially extend their lamellipodia from the corners. nu, nucleus. (C) If a cell is confined to a shape of teardrop, will the cell preferentially extend its lamellipodia from the sharp end or from the blunt end? If released from confinement, in which direction will it likely move?

Fig. 2. Asymmetric patterns polarize immobilized cells. (A) The Golgi and the centrosome are located closer to the half of a cell with the blunt end. We used phallolin, antitubulin, DAPI, antitubulin, and antipracrin to identify actin (red), the Golgi (green), the nucleus (blue), microtubules (red), and the centrosome (green), respectively. The green arrows indicate the location of centrosomes in 3T3 cells and Golgi in human umbilical artery endothelial cells (HUAEC). (B) We divided the cell into a half with the sharp end and a half with the blunt end by a vertical line drawn at the centroid of the cell. (C) The lamellipodia of immobilized 3T3 cells tended to extend more from the blunt end as well (arrowhead). The dotted line indicates the edges of the adhesive pattern.

Fig. 3. Time-lapse images (in minutes) show the motility of an initially polarized 3T3 fibroblast after its constraint is released. (A) We applied the voltage pulse at time $t = 0$. The dotted line serves as a reference for the location of the cell. (B) Another type of cell, COS-7, shows similar behavior.
Fig. 11. A series of patterns that confine cells to approximately the same projected geometry (visualized by the actin cytoskeleton) but distribute the focal adhesions (FAs; visualized by immunostaining for vinculin) differently. The bottom row shows that new focal adhesions formed 1 h after release in areas that were inert to attachment of cells prior to release (arrowheads).
Soft-Lithography

Figure 5  Schematic illustration of procedures for (a) replica molding (REM), (b) microtransfer molding (μTM), (c) micromolding in capillaries (MIMIC), and (d) solvent-assisted micromolding (SAMIM).
Electrophoresis 2002, 23, 3461–3473

A. CAD File
   └── High Resolution Printer
       └── Transparency with a pattern

B. Light
   └── Photomask
      └── Photolithography
          └── Dissolve uncrosslinked photoresist
              └── 2-layer photolithography
                  └── Light
                      └── Top master (PDMS)
                          └── Mold PDMS between masters
                              └── Bottom master (2-level photolithography)
                                  └── channel system in PDMS

C. Si
   └── Pour PDMS prepolymer, cure
       └── Peel off PDMS
           └── PDMS with negative relief channel structure

D. 500 µm
Figure 5  (a,b) Atomic force microscopy (AFM) images of Cr structures on a master and a PU replica prepared from a PDMS mold cast from this master (153). (c,d) AFM images of Au structures on another master and a PU replica produced from a PDMS mold cast from this master. (e,f) AFM images of Au structures on a third master and a PU replica fabricated from a PDMS mold (cast from this master) while this mold was mechanically deformed by bending in a manner that generated narrower lines.
Nanosphere Lithography

1. Single layer → Metal deposition → Lift-off
2. Double layer → Metal deposition → Lift-off
Array Dimension

\[ r = \frac{1}{\sqrt{3}} D \]

\[ a = \frac{3}{2} \left( \sqrt{3} - 1 - \frac{1}{\sqrt{3}} \right) D \approx \frac{1}{4} D \]

\[ r = D \]

\[ a = \left( \sqrt{3} - 1 - \frac{1}{\sqrt{3}} \right) D \approx \frac{1}{7} D \]
Optical Image of PS Template

800 nm PS
Nanosphere Lithography

350 nm

550 nm

400 nm

880 nm
Single Layer Templates

280 nm

550 nm
Double Layer Templates

400 nm

550 nm
Ordered Metal Nanohole Arrays Made by a Two-Step Replication of Honeycomb Structures of Anodic Alumina

Hideki Masuda* and Kenji Fukuda
FIG. 1. Diagram of the typical porous alumina structure when fabricated using bulk aluminum.
Project IV: Growth of 1D Nanofibers Using AAO Templates
AAO Templates

Distance (nm) vs Voltage (V)

- 30 V
- 40 V
- 50 V
- 60 V

Y = 51.8 + 1.54 * V

Graph showing the relationship between distance (nm) and voltage (V).
Submicrometer Metallic Barcodes

Sheila R. Nicewarner-Peña, R. Griffith Freeman, Brian D. Roiss, Lin He, David J. Peña, Ian D. Walton, Remy Cromer, Christine D. Keating, Michael J. Natan

1. $\text{Au}^+ + e^- \rightarrow \text{Au}$ x Coulombs (C)
2. $\text{Ag}^+ + e^- \rightarrow \text{Ag}$ x C
3. $\text{Au}^+ + e^- \rightarrow \text{Au}$ 2x C
4. $\text{Ag}^+ + e^- \rightarrow \text{Ag}$ x C
5. $\text{Au}^+ + e^- \rightarrow \text{Au}$ x C

1. $\text{Au}^+ + e^- \rightarrow \text{Au}$ x C
2. $\text{Ag}^+ + e^- \rightarrow \text{Ag}$ 2x C
3. $\text{Au}^+ + e^- \rightarrow \text{Au}$ 3x C

1. Ag film dissolution with HNO$_3$
2. Al$_2$O$_3$ dissolution with NaOH
X-ray Diffraction

4-Circle Goniometer (Eulerian or Kappa Geometry)

Bragg Law

$$2d \sin \theta = \lambda$$

where:
- $d$ = lattice interplanar spacing of the crystal
- $\theta$ = x-ray incidence angle (Bragg angle)
- $\lambda$ = wavelength of the characteristic x-rays
Miller Index

\[ \ell b_1 + m b_2 + n b_3. \]

\[(hkl) = h\vec{a}^* + k\vec{b}^* + l\vec{c}^* = \frac{2}{3a^2}(2h + k)\vec{a} + \frac{2}{3a^2}(h + 2k)\vec{b} + \frac{1}{c^2}(l)\vec{c}. \]
Scherrer Equation

\[ \beta_{hkl} = \frac{K \lambda}{L_{hkl} \cos \theta_{hkl}} \]

Scherrer formula:

\[ t = \frac{0.9 \lambda}{B \cos \theta} \]

- \( t \): particle size
- \( B \) (width): in radians, at an intensity equal to half the maximum intensity.

Graph showing an X-ray diffraction pattern with peaks at 2\( \theta \) values of 12°, 12.4°, and 12.8°, labeled as (202), (022), (311), and (131).
CVD Carbon Nanotube
**LP CVD**

---

**Figure 17**
SEM cross-section micrograph illustrating gap filling and local planarization of a shallow-trench isolation structure, achieved using HDP-CVD of silicon oxide.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>ΔH (kJ/mole)</th>
<th>Conformality</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiH₄  ( \rightarrow ) Si + 2H₂</td>
<td>-34</td>
<td>spectacular</td>
</tr>
<tr>
<td>WFs + 3H₂ ( \rightarrow ) W + 6HF</td>
<td>-111</td>
<td>spectacular</td>
</tr>
<tr>
<td>TEOS ( \rightarrow ) SiO₂ + 2C₂H₄ + 2CH₃CH₂OH</td>
<td>(small)</td>
<td>excellent</td>
</tr>
<tr>
<td>3SiH₄ + 4NH₃ ( \rightarrow ) Si₃N₄ + 2H₂</td>
<td>-374</td>
<td>good to excellent</td>
</tr>
<tr>
<td>SiH₄ + 2O₂ ( \rightarrow ) SiO₂ + 2H₂O</td>
<td>-1564</td>
<td>mediocre</td>
</tr>
</tbody>
</table>
Atomic Layer Deposition

Conditioned surface → Precursor (TMA) dosing → Purge step

Reducing agent (H₂O) → Purge step
MBE
Template Synthesis
Sol-Gel Technologies and Their Products