# Redefine Optical Devices' Integration and Manufacturing through Nano-engineering

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*April 23, 2005*
*WOCC 2005*
*Newark, NJ*

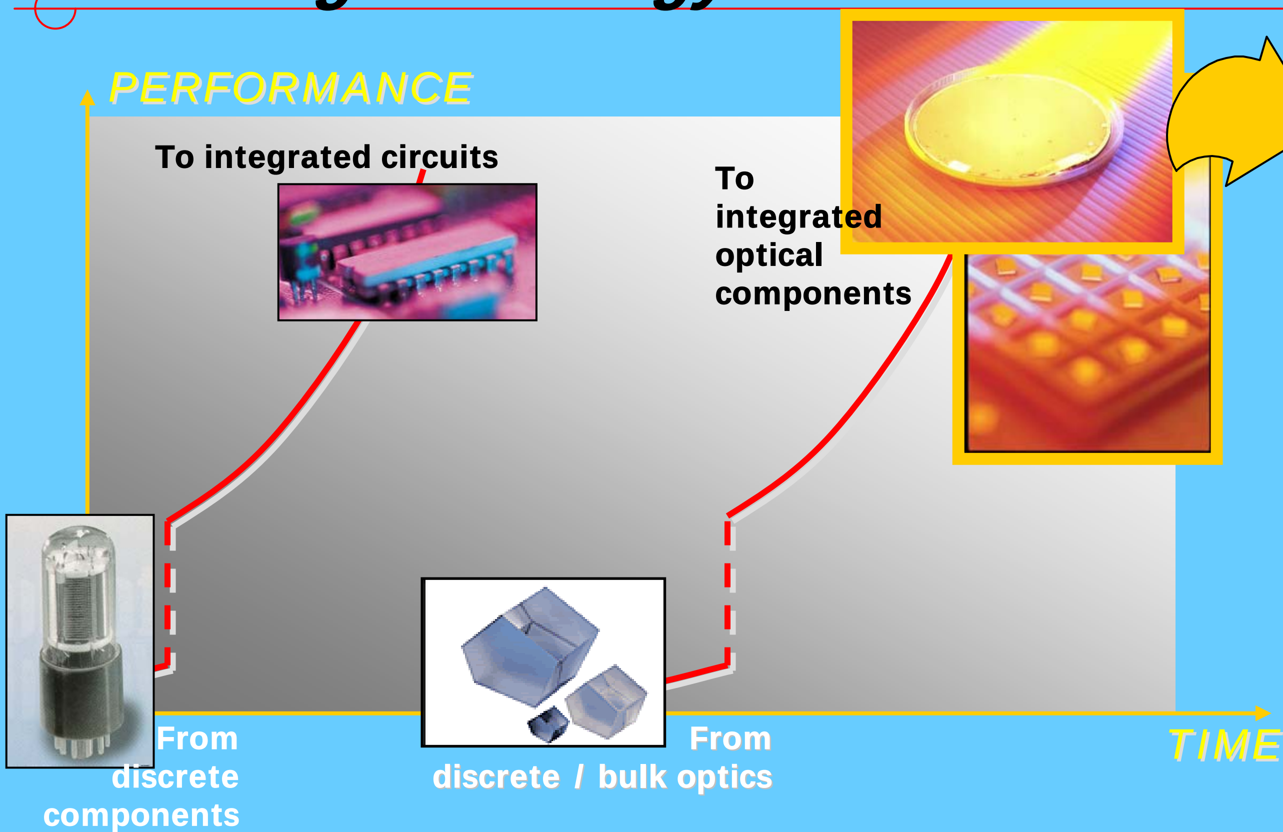
# Optics, a déjà vu of Electronics...

**"Here we were in a factory that was making all these transistors in a perfect array on a single wafer and then we cut them apart into tiny pieces and had to hire thousands of women with tweezers to pick them up and try to wire them together. It just seemed so stupid. It's expensive, it's unreliable, it clearly limits the complexity of the circuits you can build. It was an acute problem. The answer was, of course, don't cut them apart in the first place. But nobody realized that then."**
**- Robert Noyce**

| "Tyranny of Numbers" | Applied to Optics |
| --- | --- |
| ⇩ Manual assembly | Dominates optical circuit manufacture and costs |
| ⇩ Interconnection inefficiency | Increases power requirements, limits applications |
| ⇩ Limits to reliability | Requires tolerance balancing and limits functionality |
| ⇩ Limits in design complexity | Reduces functionality and raise cost |

**Drivers:** Size, Cost, Reliability, Functionality

# *Integrated optics is a broadly enabling technology*

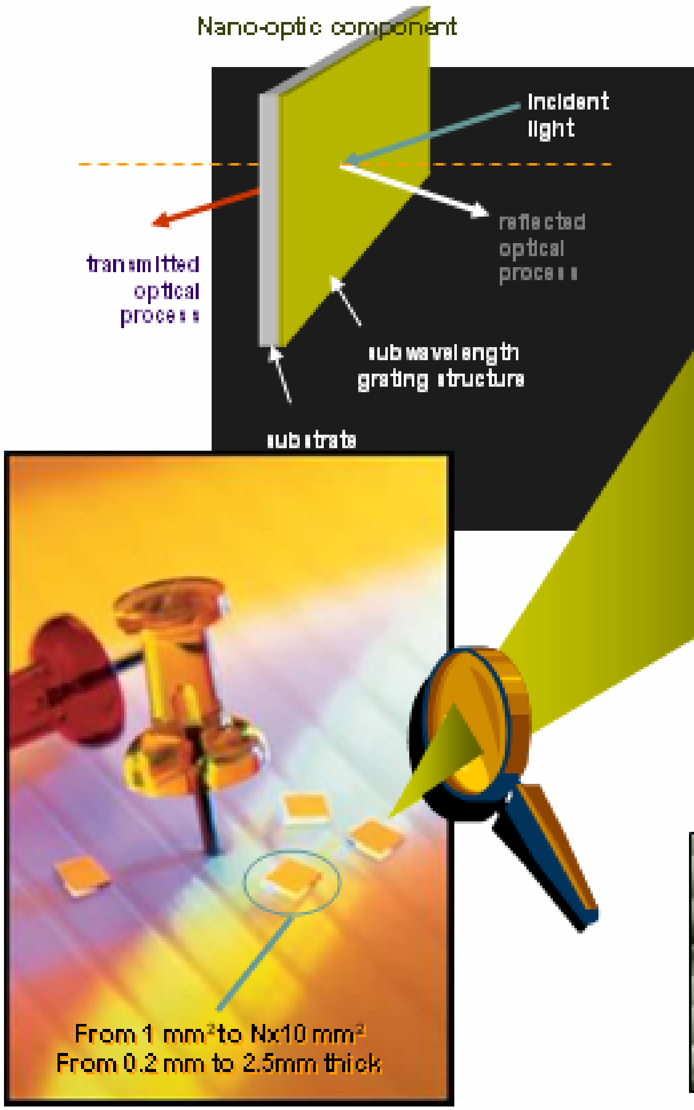


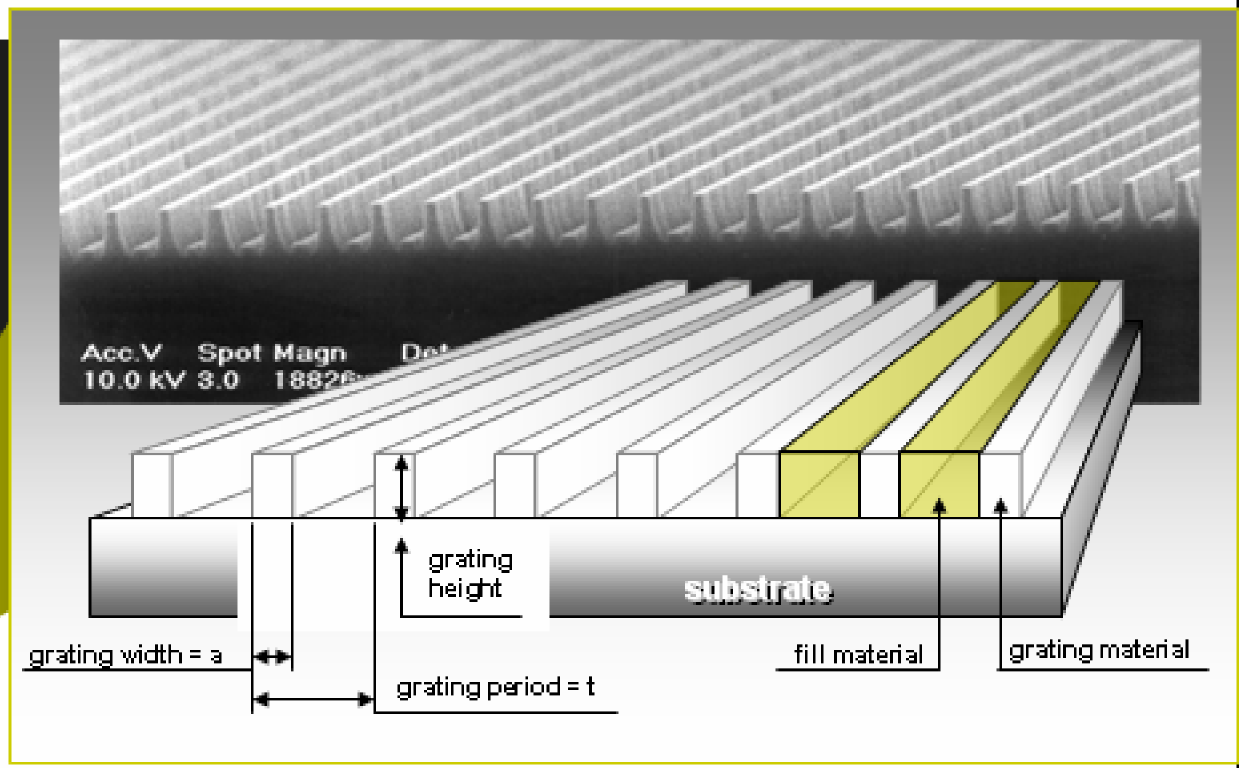

**Criteria for Success:**

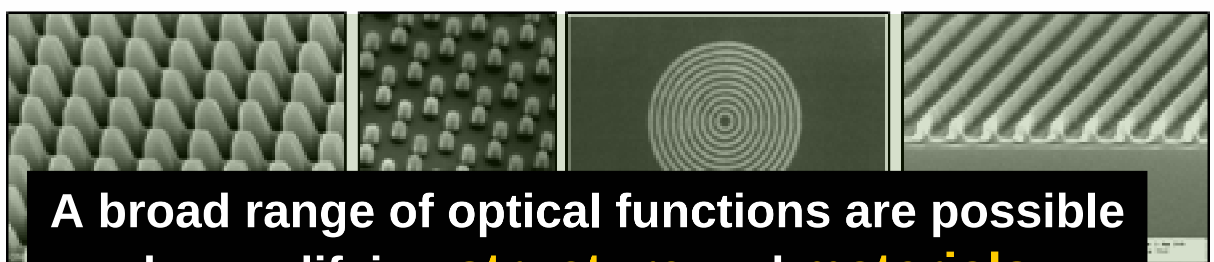
1. Building block technology
2. Means for integration
3. High volume production capability

- Optical circuits are applied in a broad range of industries
- There is a continuing requirement to improve cost and capability in all applications

# Nano-structures modify material properties...



**A broad range of optical functions are possible by modifying structure and materials**

# *Why nano-optics?*

- **Patterning material on a nano-meter scale allows us to tailor the fundamental optical properties by controlling**
  - Geometry
  - Materials
  - Integration

- **The resulting optical devices change the cost / capability equation for optical components via**
  - New functionality
  - New architectural possibilities
  - Lower cost through self-integration
  - Lower cost by integrating with other technologies
  - Lower cost through ease of assembly
  - Lower cost through higher volumes

# *Nano optic enabled functions*

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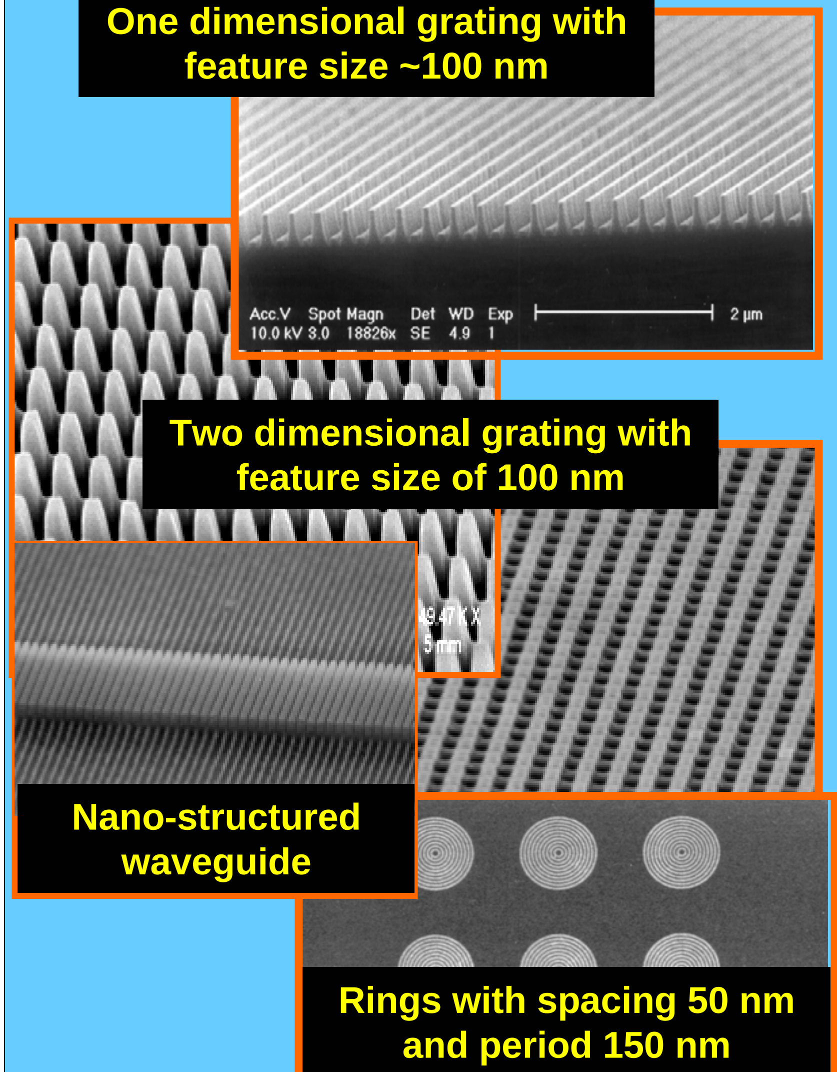
Improving performance through nano engineering




One dimensional grating with feature size ~100 nm

Two dimensional grating with feature size of 100 nm

Nano-structured waveguide

Rings with spacing 50 nm and period 150 nm

- **Polarization Management**
  - **Polarizers**
  - **Polarization beam splitters / combiners**
- **Phase Management**
  - **True zero-order waveplates**
  - **Trim retarders**
- **Wavelength Management**
  - **Notch and square-top filters**
  - **Fixed and tunable filters**
- **Focal Management**
  - **Waveguides**
  - **Anti-reflective coatings**
  - **Lens arrays**

**Wavelength**

NIR
(1000 – 3000 nm)

Near IR
(700 – 1000 nm)

Visible
(400 – 700 nm)

UV
(sub 400 nm)

# *Nano-lithography Overview*

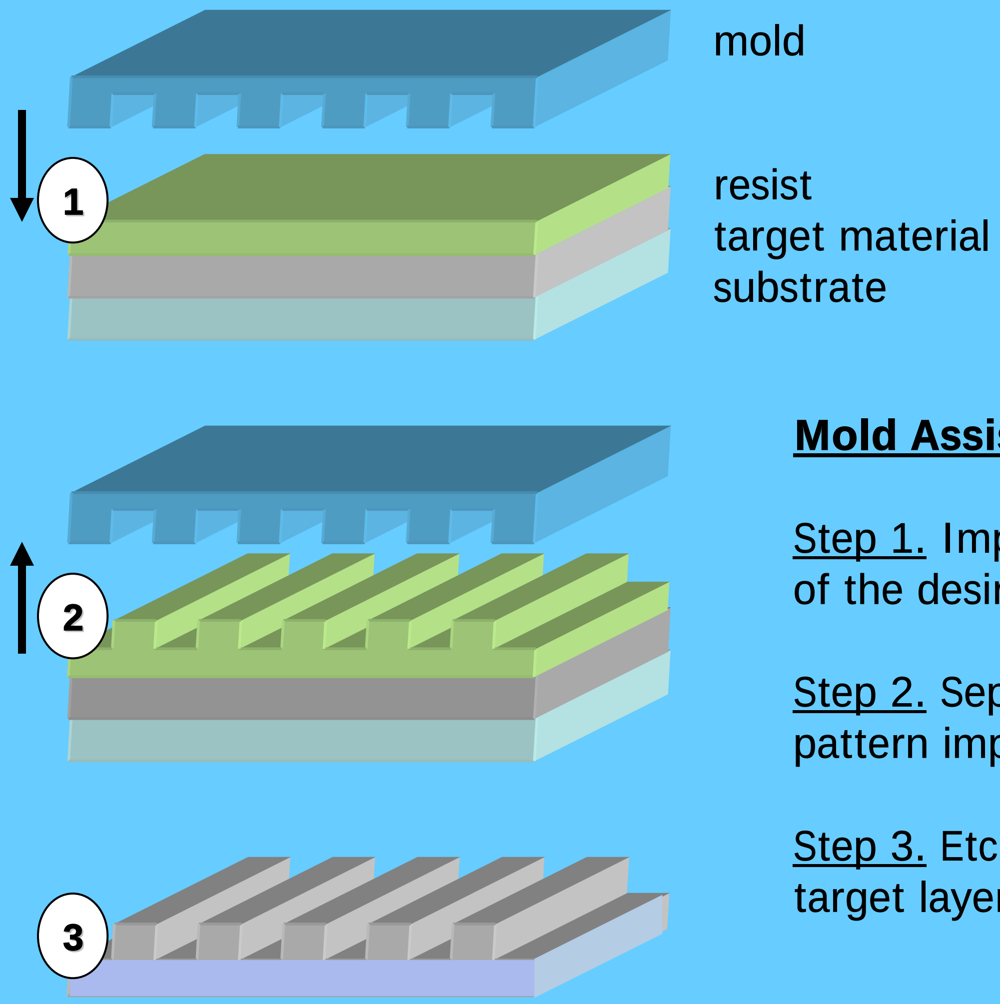
- Conventional nano-lithography
  - Photolithography

| Generation | Wavelength (nm) | Minimal Linewidth (nm) |
|---|---|---|
| G | 436 | 145 |
| I | 365 | 122 |
| KrF | 248 | 83 |
| ArF | 193 | 64 |
| F2 | 157 | 53 |
| EUV | 13.5 | 16 |

  - 10 years and $10 billions investment between each generation
  - Currently 193 nm, chemically amplified resist, 80 nm resolution, 100 wafers (300mm) per hour, 26 x 32 mm field: $40M/tool
  - X-ray lithography (EUV)
  - E-beam lithography
  - Ion-beam lithography

- Non-conventional nano-lithography
  - Mold assisted lithography (nanoimprint, embossing, NPT, ...)
  - Nano-pen lithography (AFM based ...)
  - Soft-lithography (George Whitesides, Havard)

# Mold Assisted Lithography



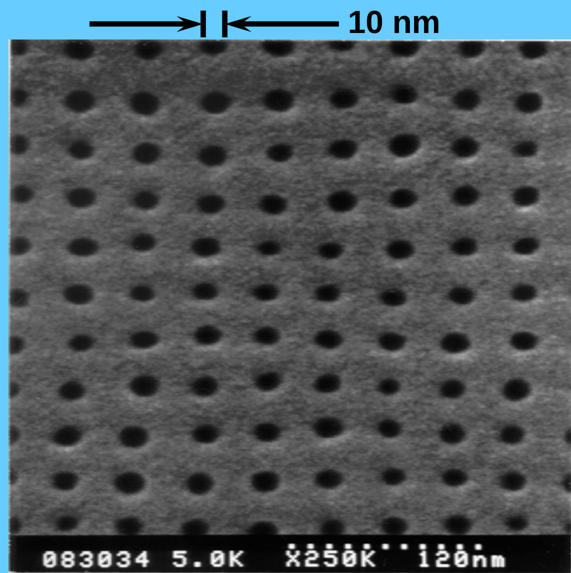

**Mold Assisted lithography primer:**

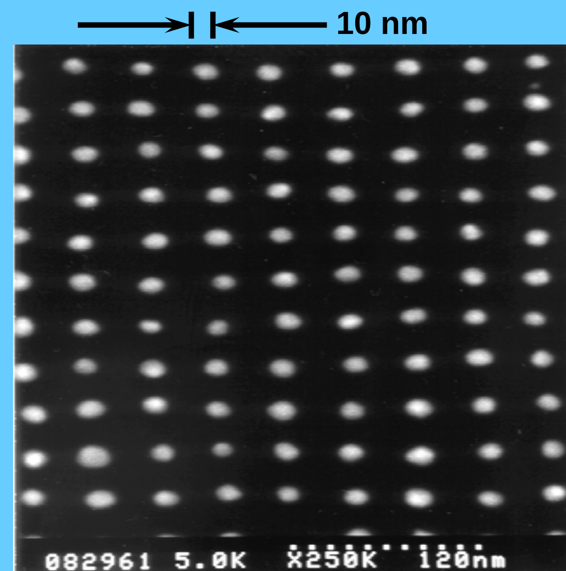
Step 1. Impress mold containing negative of the desired structure.

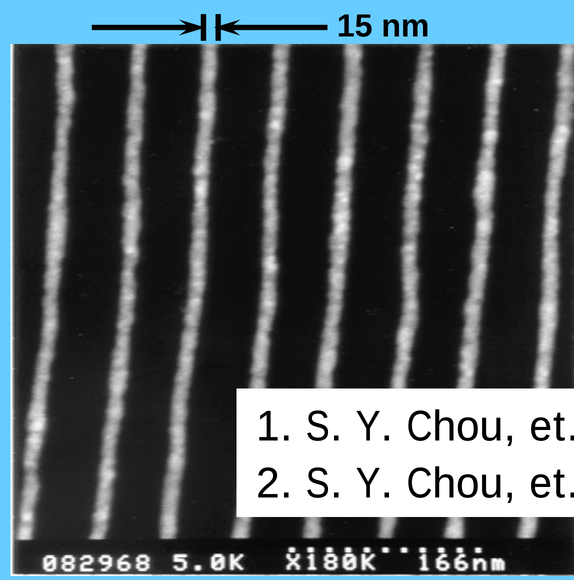
Step 2. Separate mold, leaving nano-pattern impression in resist.

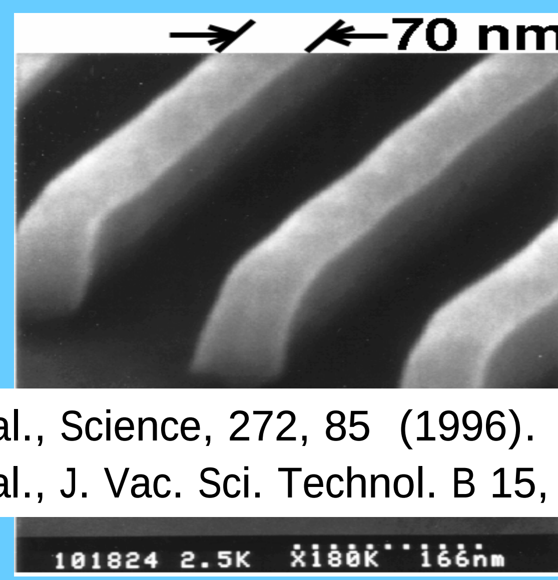
Step 3. Etch resist to transfer pattern to target layer.

# *Resolution is non-issue*



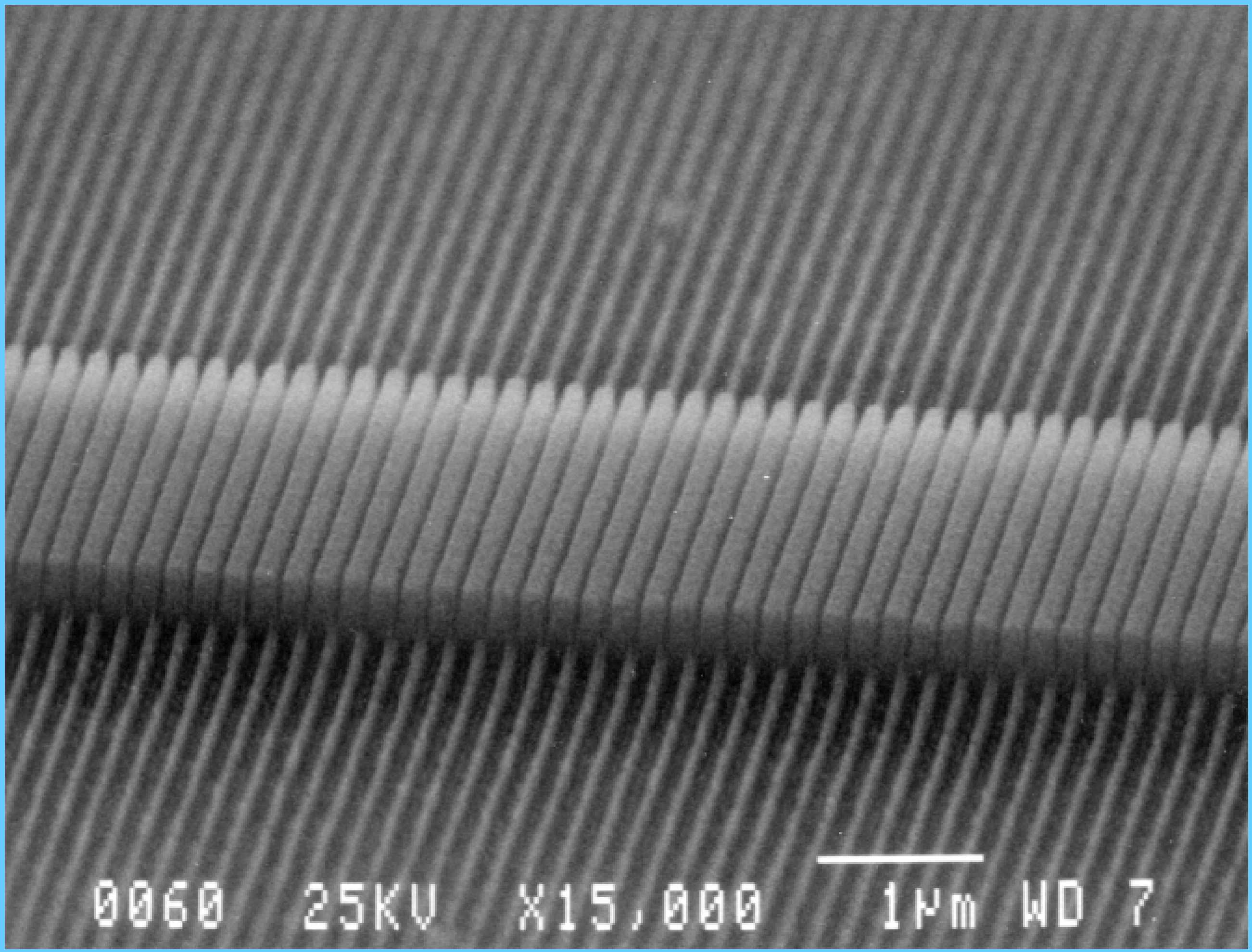




1. S. Y. Chou, et. al., Science, 272, 85 (1996).
2. S. Y. Chou, et. al., J. Vac. Sci. Technol. B 15, 2897 (1996).

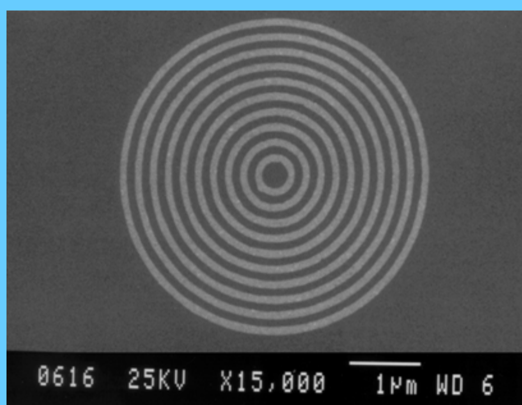
# *A Waveguide DFB/DBR Structure by Nano-imprint Lithography*



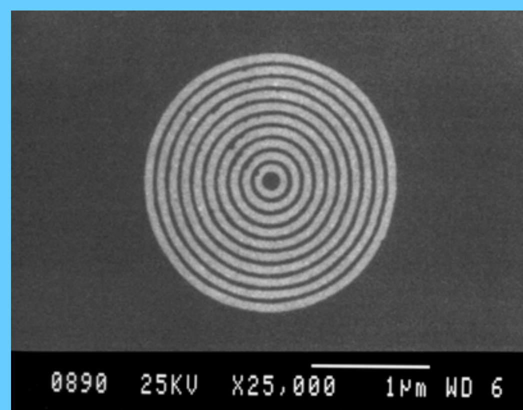

J. Wang et. al., J. Vac. Sci. Tech., 17 (6) 2957-2960 (1999).

# *Random Patterns*

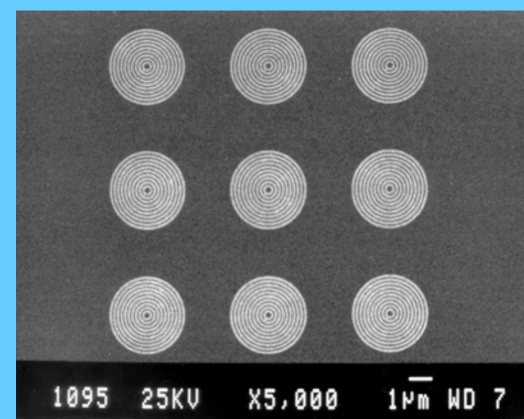
Spacing: 100 nm
Period: 200 nm




Spacing: 20 nm
Period: 100 nm




Spacing: 50 nm
Period: 150 nm




M. T. Li, J. Wang, L. Zhuang, and S. Y. Chou, Appl. Phys. Lett., 76 (6), pp. 673-675 (2000).

# *Nano-pattern Replication Machine*

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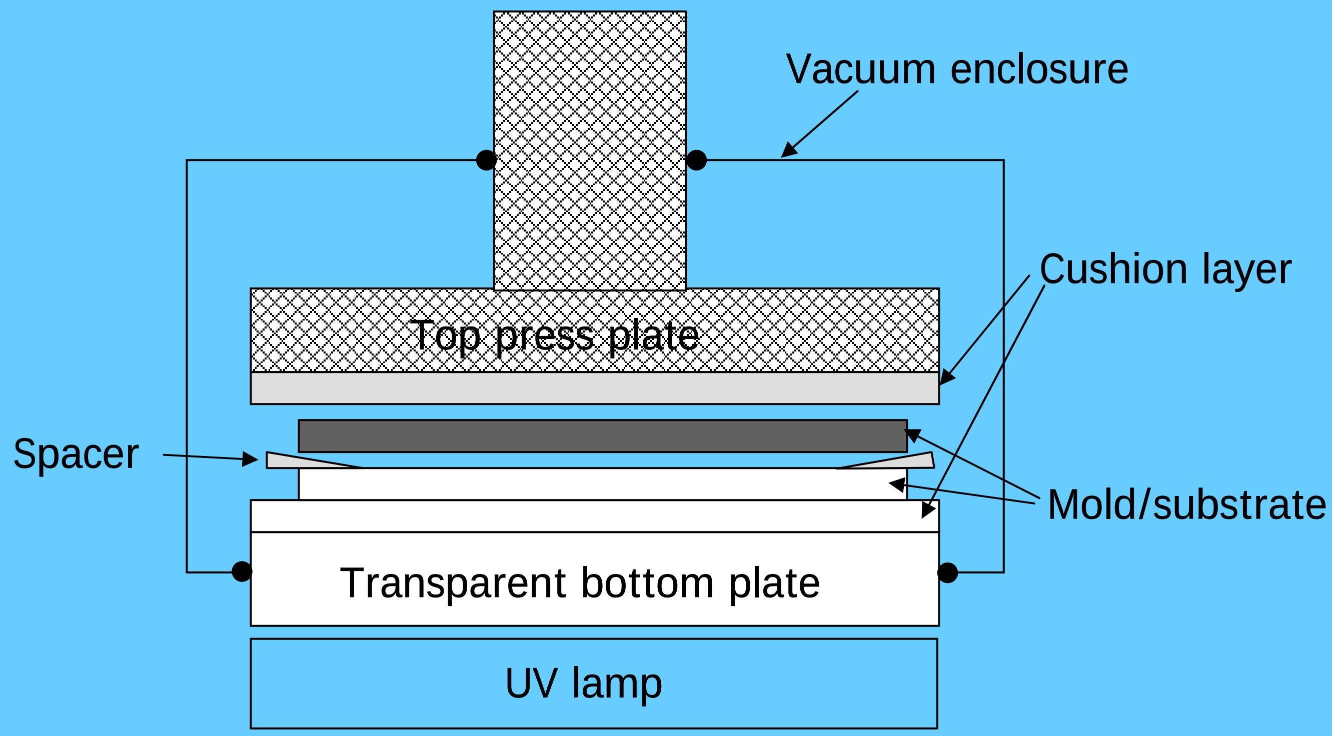
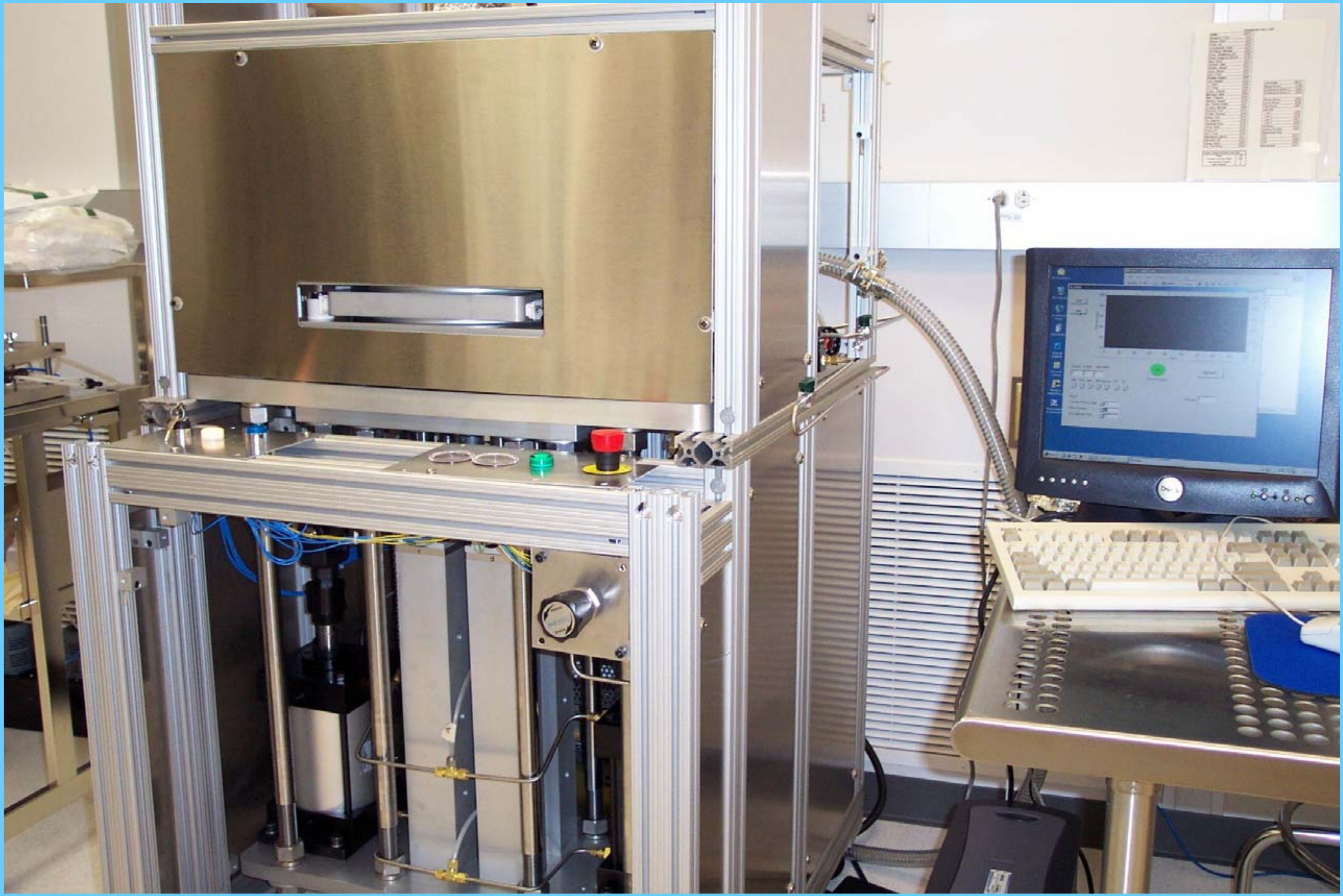



- **6” whole wafer patterning capability**
- **Uniform nano-pattern replication ensured by both spin-coating process and cushion layer design**
- **High throughput process: 30 wafers/hour throughput, only 5 seconds UV curing**
- **Scalable design: 8”, 12”**

J. Wang, L. Chen, S. Tai, D. Deng, P. Sciortino, J. Deng, and F. Liu,
“Wafer based nano-structure manufacturing for integrated nano-optic devices,”
J. Lightwave Technology, Vol. 23, No. 2, 474 – 485 (2005).

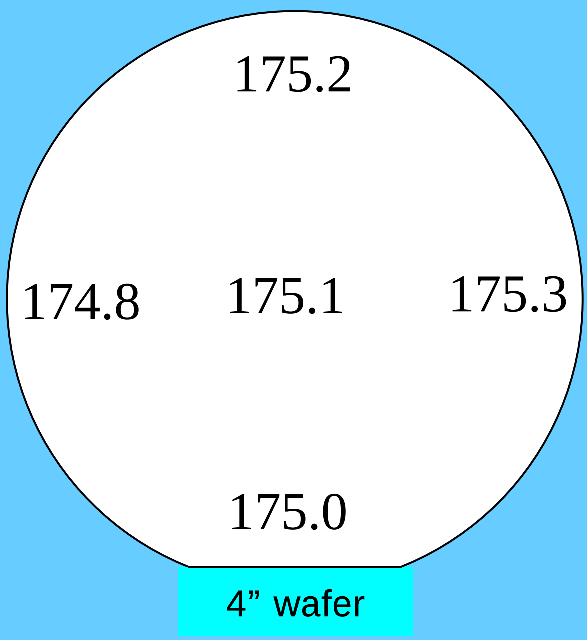
# *Nano-pattern Replication Tool Development*

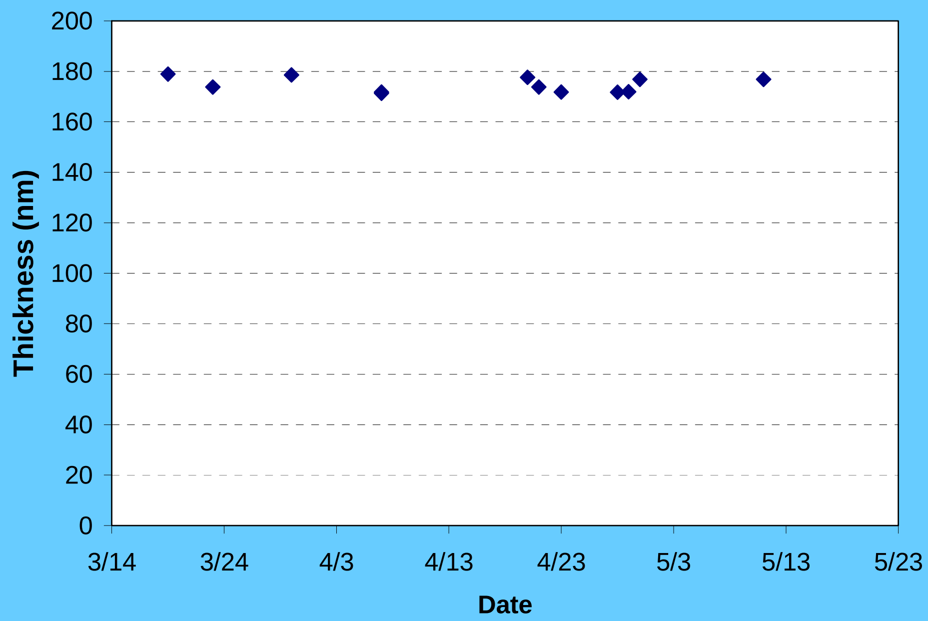


# *Single-layer Spin Coated UV Curable Resist for Nano-pattern Replication*

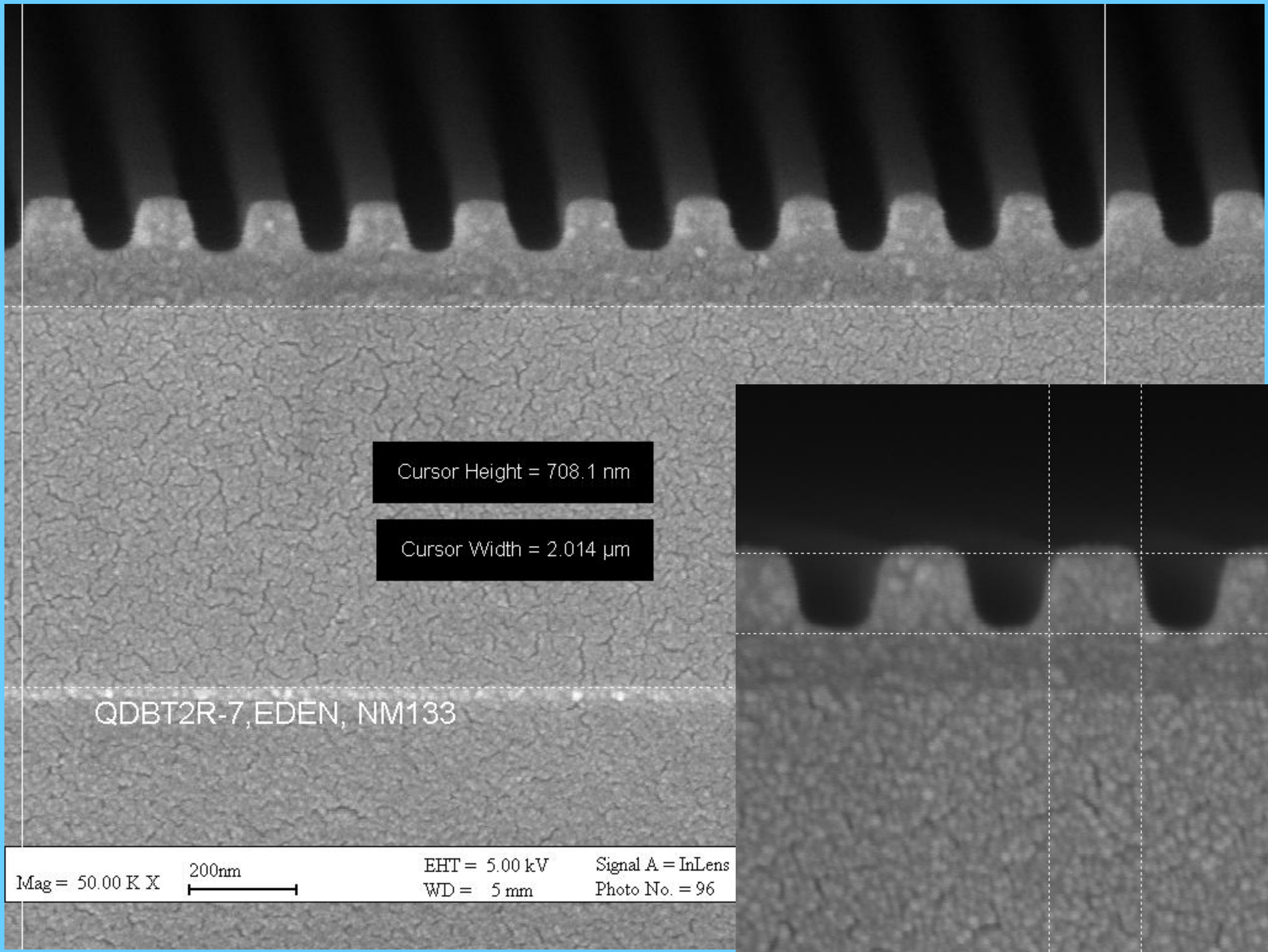
- Low-viscosity UV curable resin as resist for nano-pattern replication
- Spin coat compatible single layer process directly onto substrate (glass, silicon, GaAs, InP…)
- Can be spin coated very uniformly: comparable to photoresist
- Fast UV curing speed: 5 seconds
- Post-cured resist with excellent mechanical, thermal, chemical and etching properties
- Lift-off capable

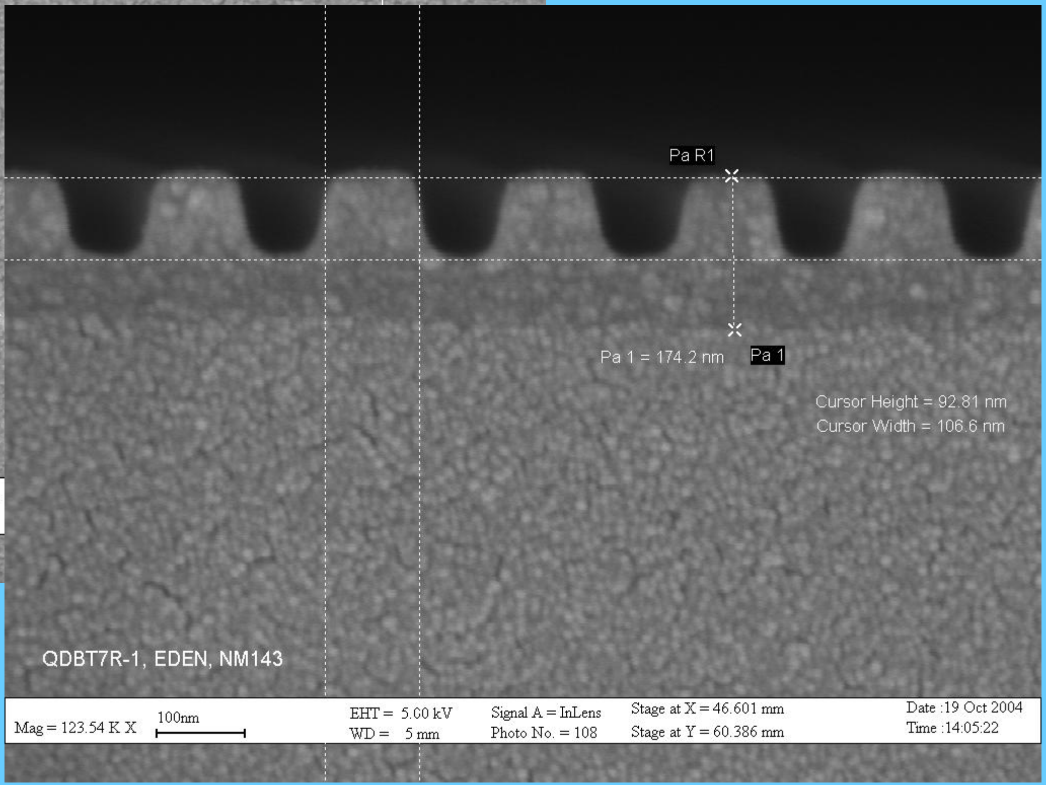
In nanometers



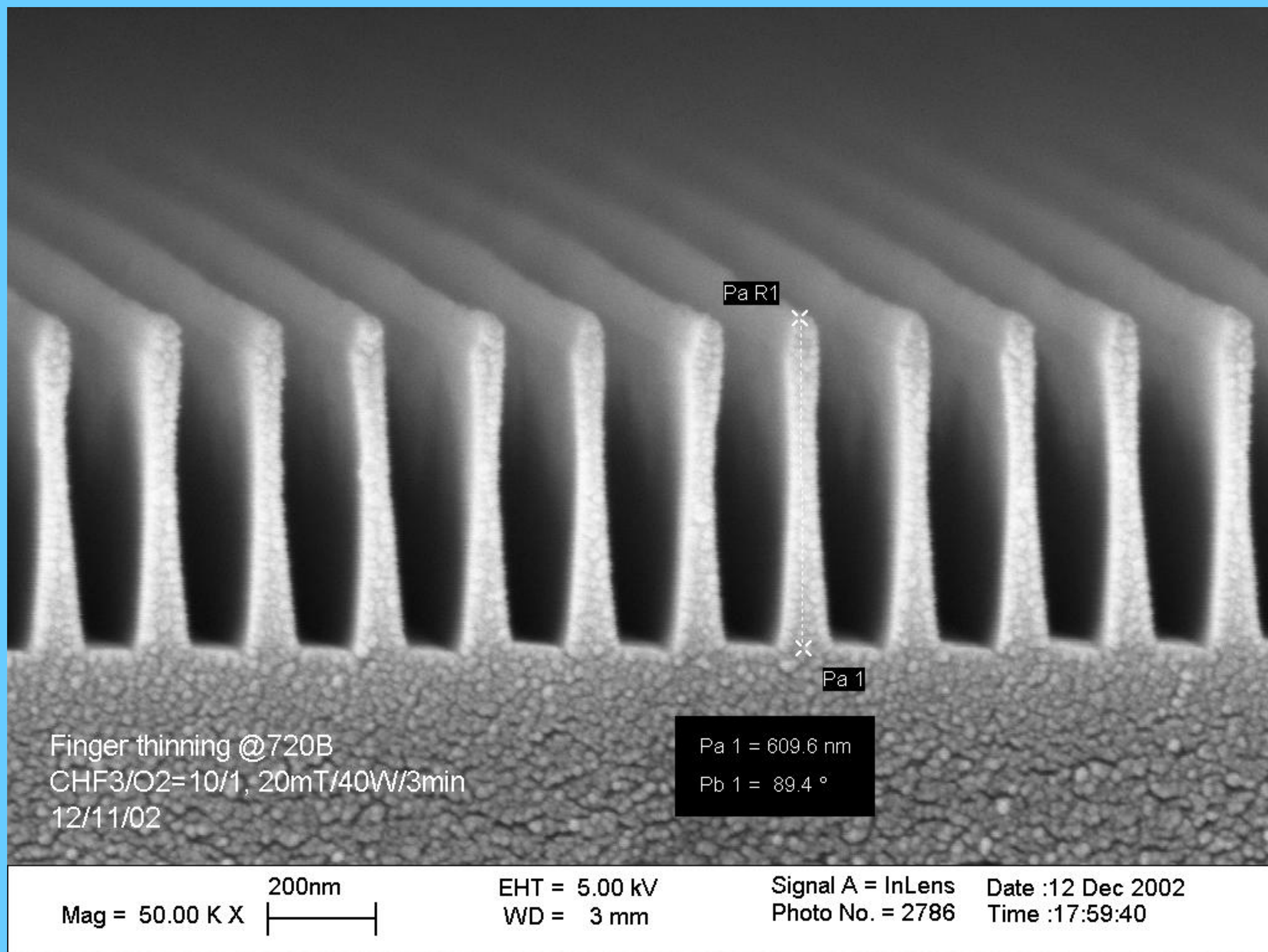



# *Right after nano-pattern replication …*



# Deep RIE ...SiO2 Gratings (I)



## Nano-optic Polarizers / Polarizing beam splitter / combiner – Integration is the key for our vision

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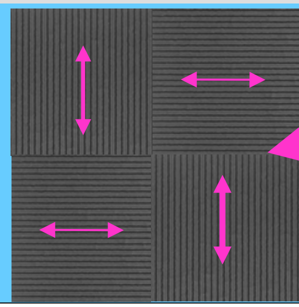
Improving performance through nano engineering

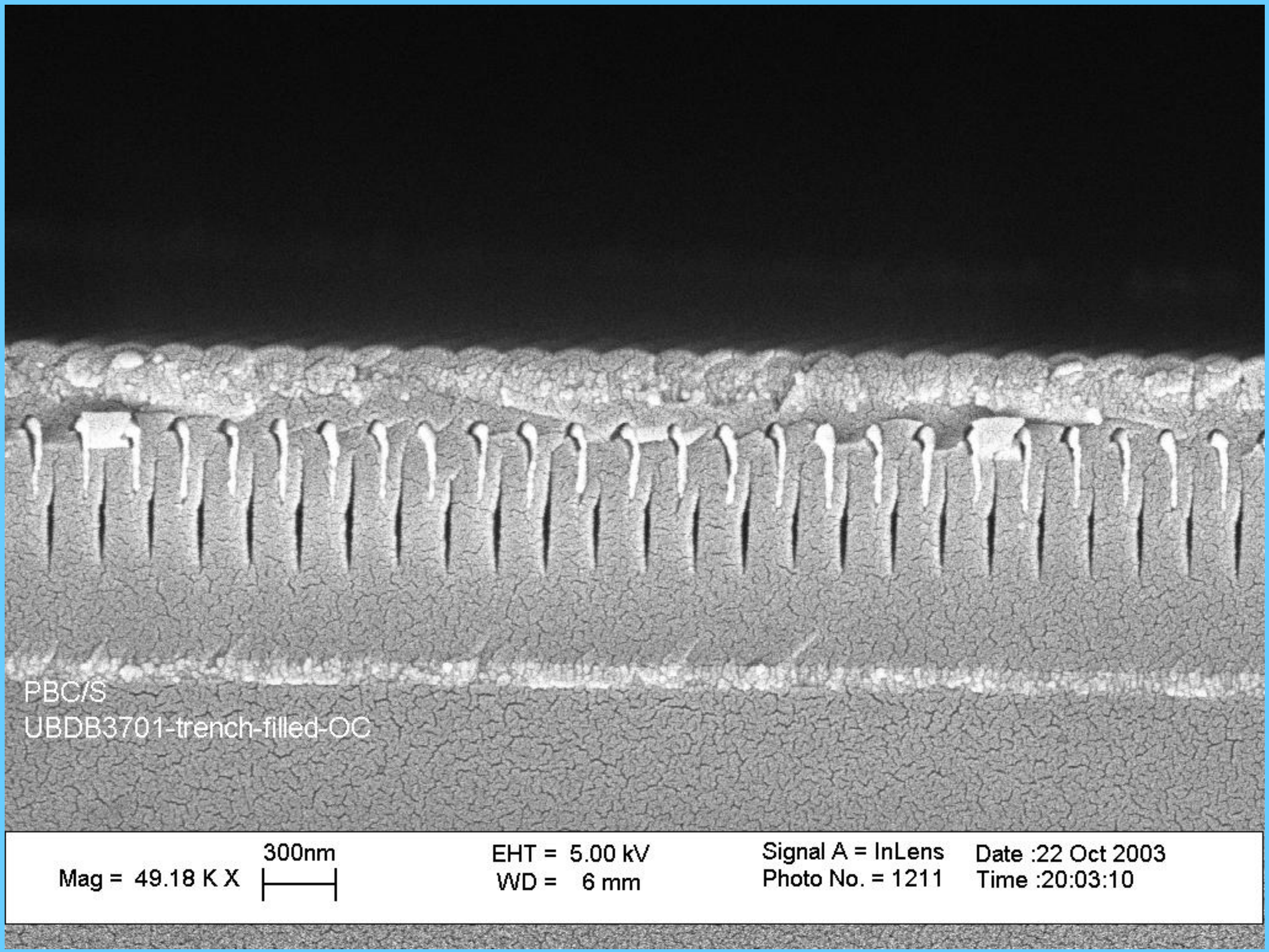
- Excellent performance:
  - Broadband (ARC dependent) from 1200 nm to > 1800 nm
  - > 98% transmission (< 0.1 dB), > 43 dB extinction ratio
- Only < 1 µm in total (active layer) thickness
- Fully compatible semiconductor manufacturing process
- Currently 4” in-diameter wafer process, can be upgraded to 8” to 12”
- Can be integrated onto almost anything:
  - garnet, $LiNbO_3$, YAG, $YVO_4$, InP, Si, GaAs….
- Can be fabricated onto crystal facets, laser facets, VCSEL surfaces
- The blocked polarization is highly reflective (> 97% reflection)
  - a perfect broadband polarization mirror,
  - excellent as laser mirrors for VCSELs and edge-emitting lasers
- Low-cost thanks to semiconductor process: ~ $0.01/mm$^2$
- Pixellated polarizer array: excellent for array applications

50 µm thin
4”-size polarizer:
So thin to be bendable



A pixellated polarizer

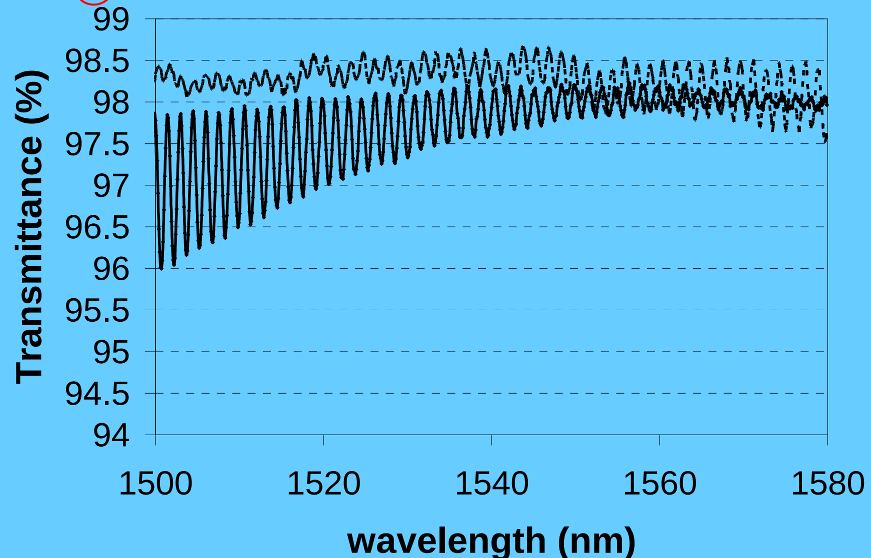
# Telecom Polarizer

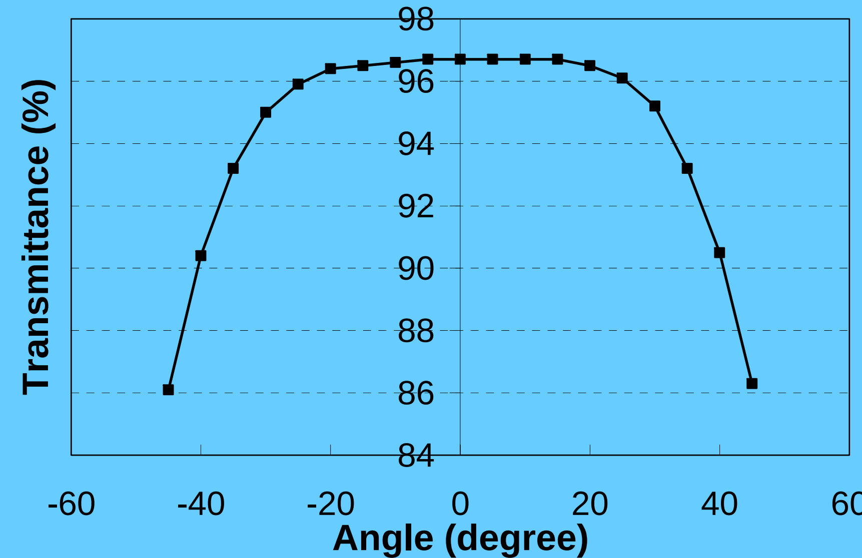


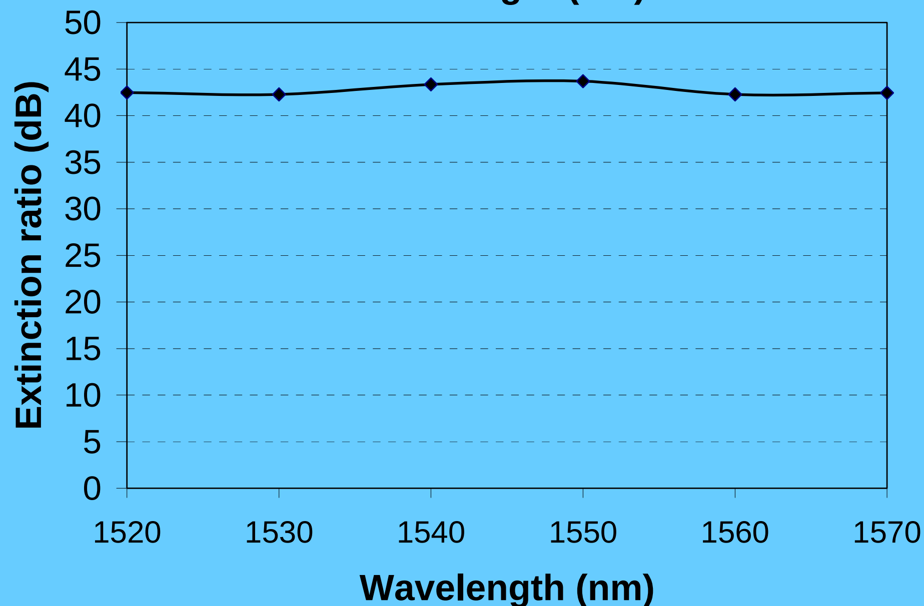
# Performance Comparison With CuPo™ and PolarCor™

| Performance | CuPo™ | PolarCor™ | NanoOpto |
|---|---|---|---|
| Transmittance / Insertion loss | < 0.1 dB<br>1310, 1480, 1550 nm | 98% (<0.1 dB)<br>1310, 1480, 1550 nm | 98% (< 0.1 dB)<br>1310, 1480, 1550 nm |
| Extinction ratio / Isolation | > 40 dB | > 40 dB | > 40 dB |
| Size and thickness | Max Size N/A<br>0.2 mm thick | Max. 15 mm x 15 mm<br>0.2 mm thick | 100 mm x 100 mm<br>0.2 mm, 0.1 mm and thinner |
| Notes | • Active-layer thickness ~ 30 µm<br>• Two surfaces for 40 dB<br>• Lower power handling due to absorptive blocking<br>• Light scattering issue due to nano-particles | • Active-layer thickness ~ 30 µm<br>• Two surfaces for 40 dB<br>• One surface only offers 23 dB<br>• Lower power handling due to absorptive blocking<br>• Light scattering issue due to nano-particles<br>• Potential environment issue of manufacturing method | • Active-layer thickness: ~ 1 µm<br>• One surface coating<br>• Higher power handling capability due to reflective blocking<br>• No light scattering issue, proved by customer<br>• Environment friend manufacturing method |

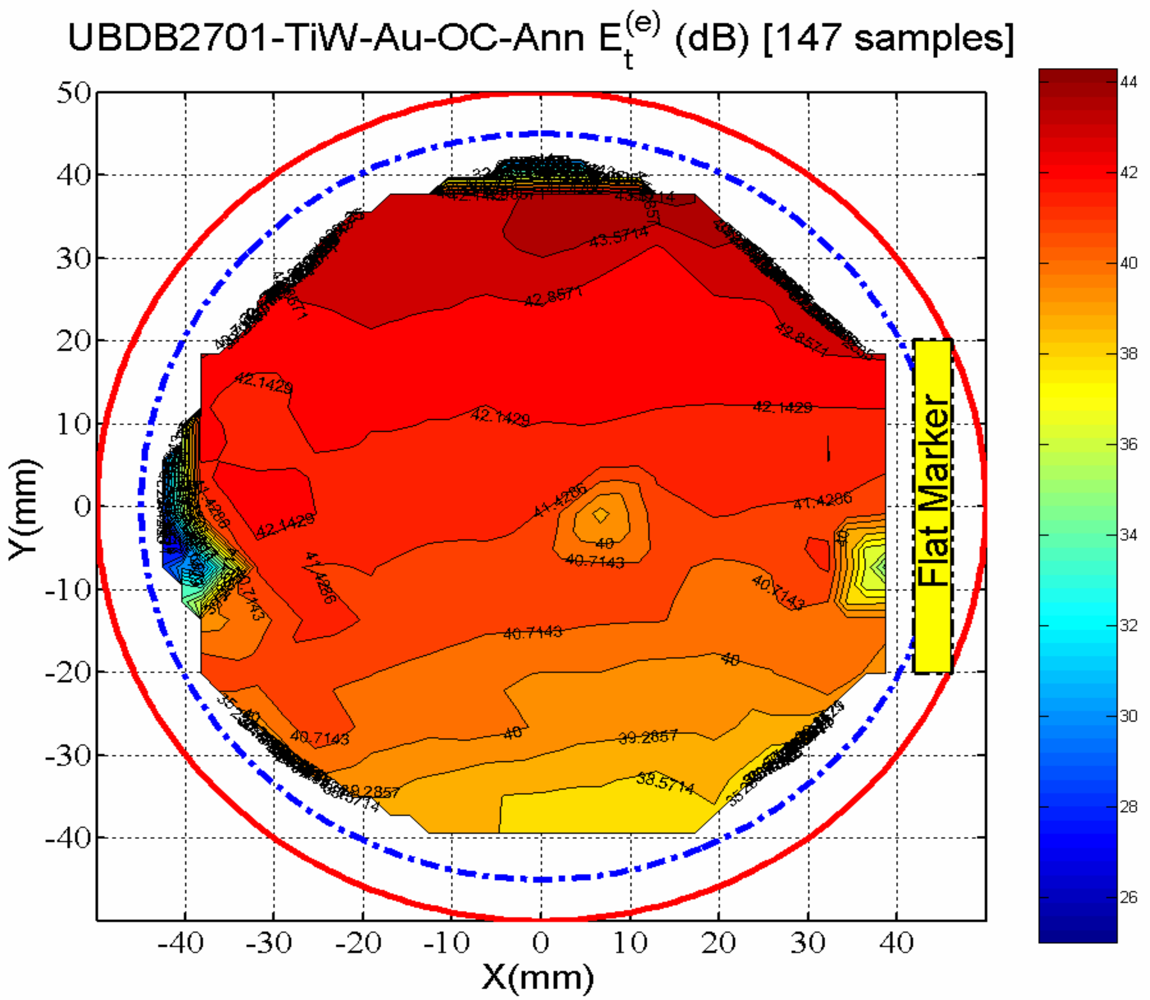
# *Performance of the nano-wire-grid polarizer*



# *4"-wafer Telecom Polarizer: Extinction Ratio*



# *4" nano-wire-grid polarizer wafers: performance distribution*

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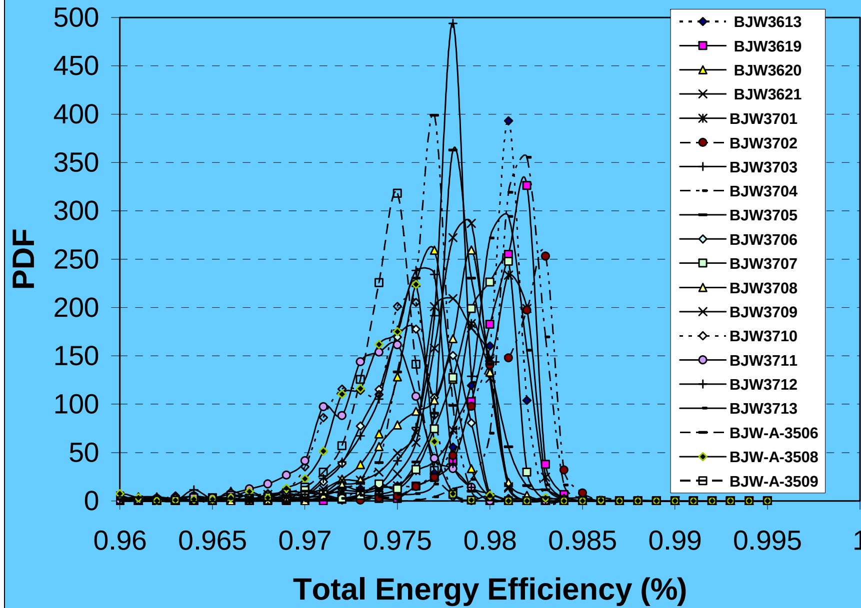
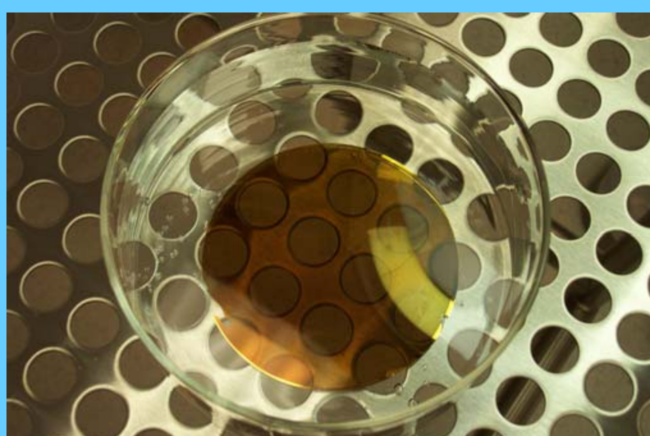
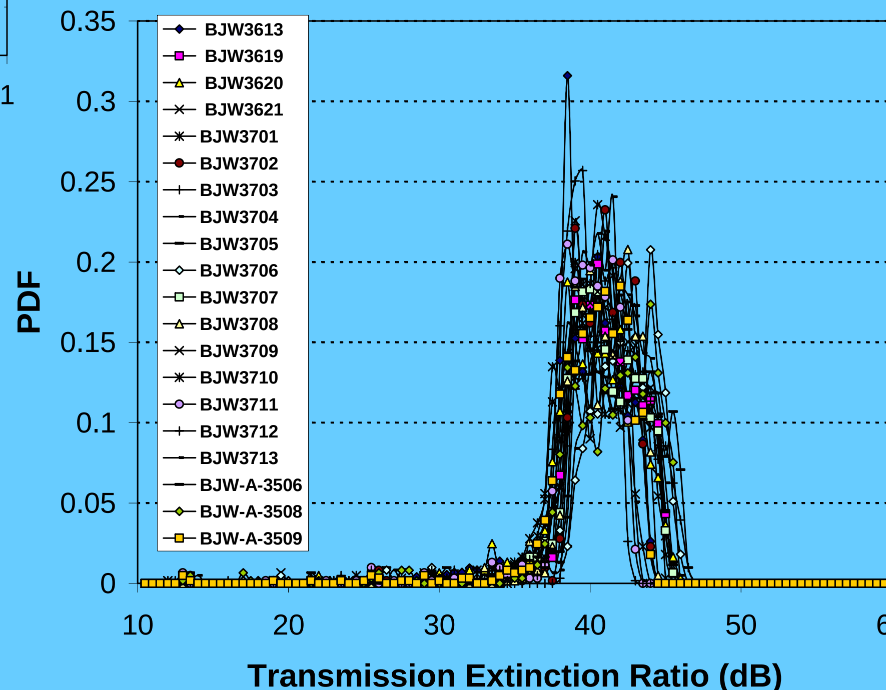
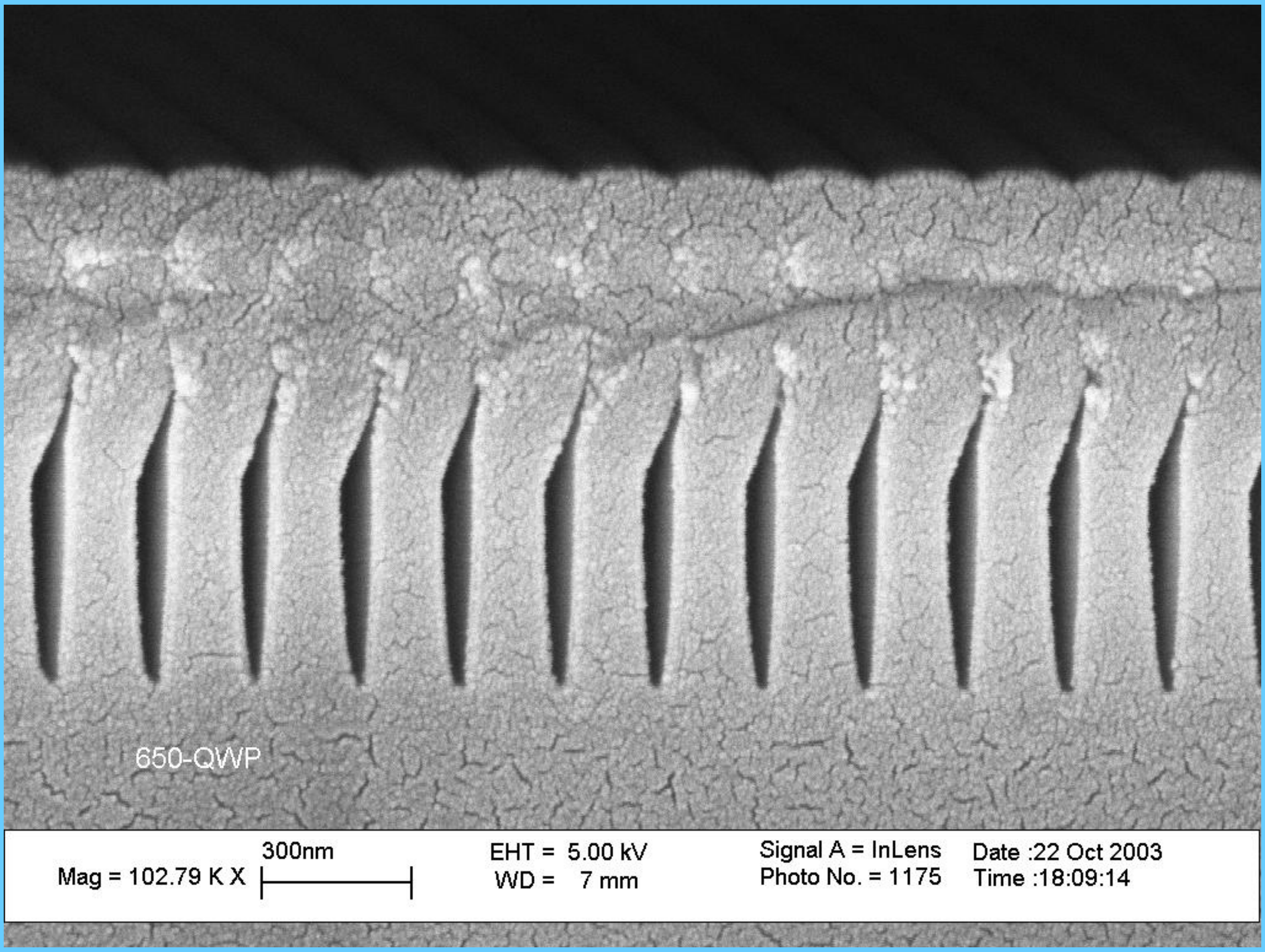


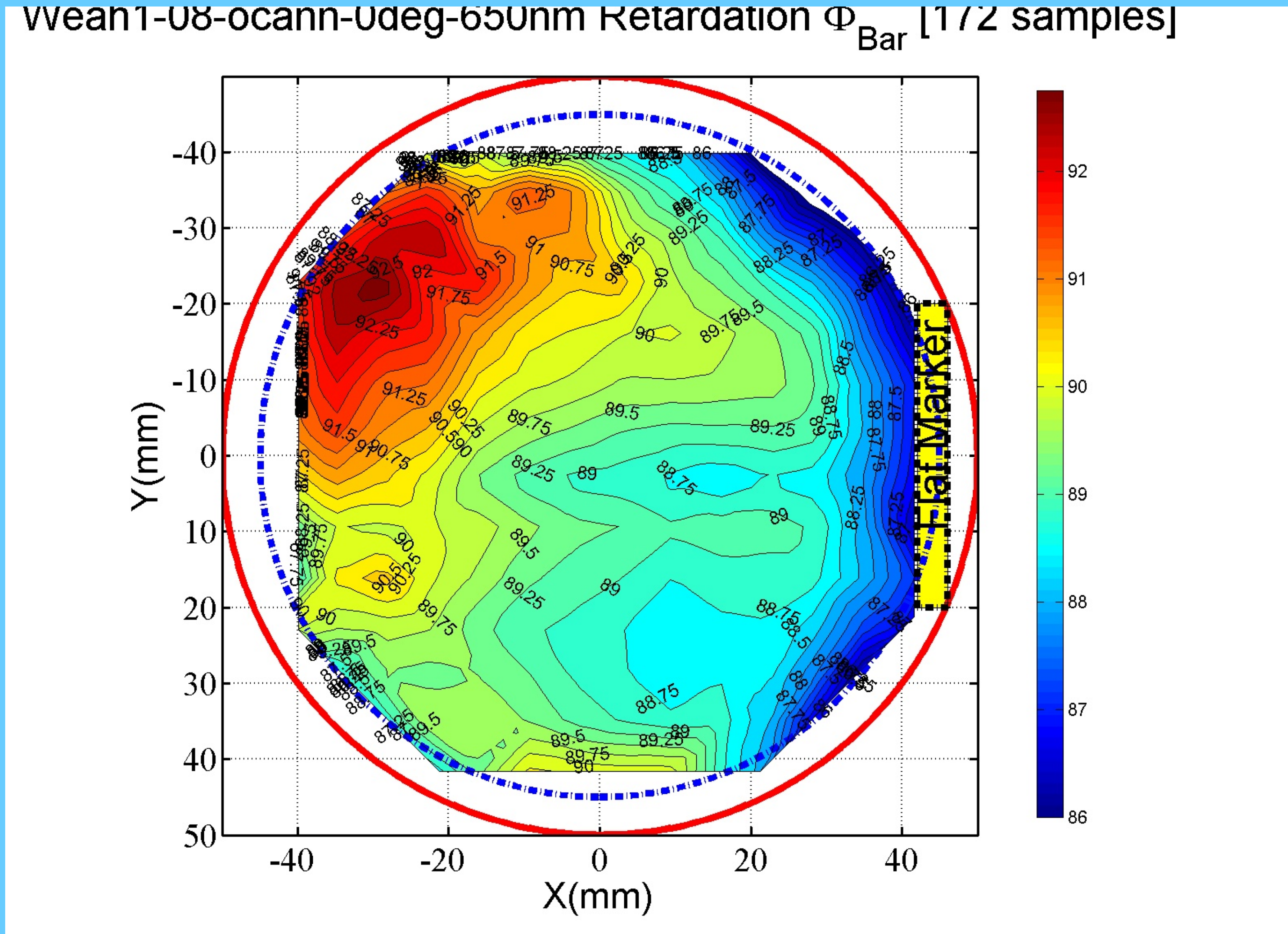



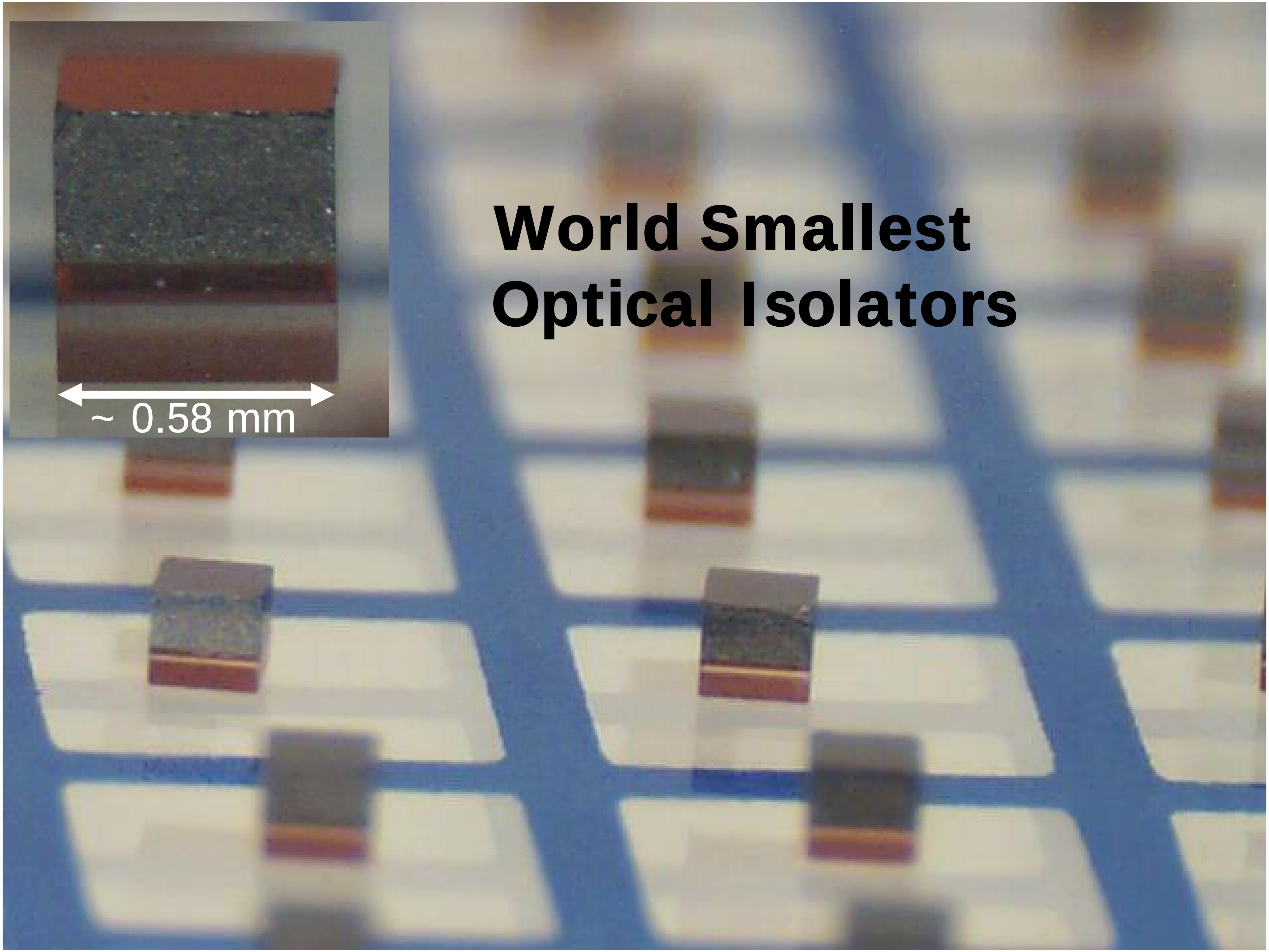


# A complete quarter-wave-plate for DVD Optical Head



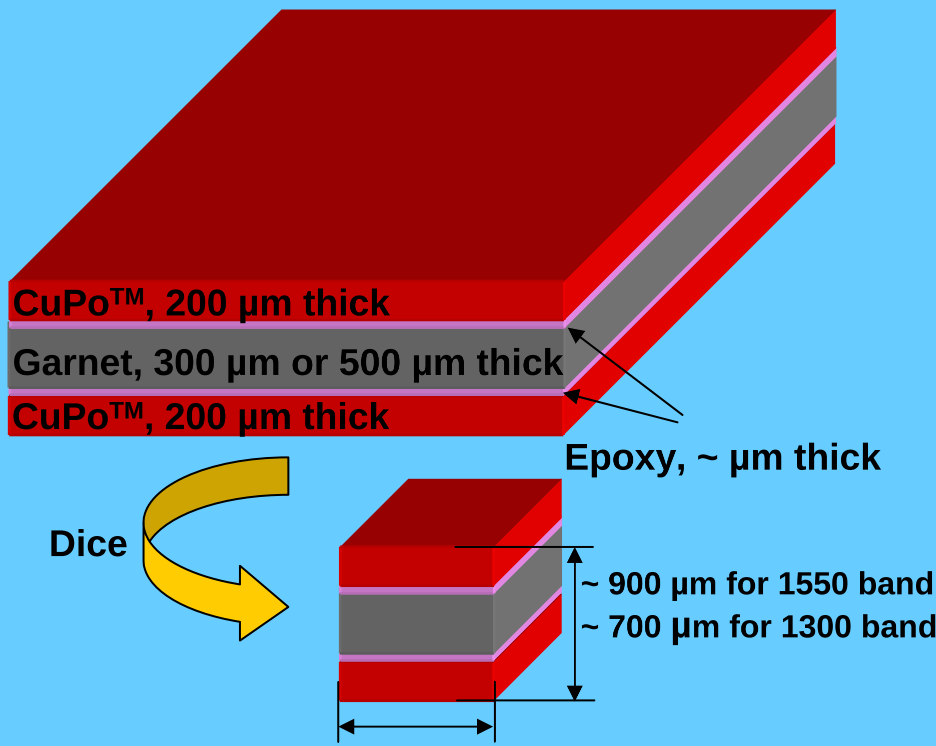
# *4”-wafer DVD quarter-wave-plate: Phase Retardation*



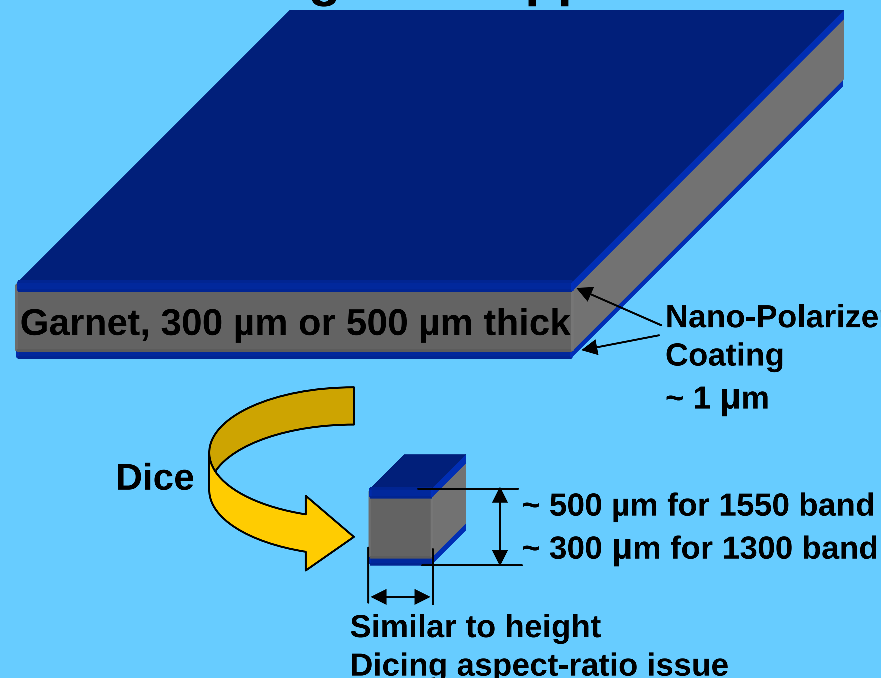

~ 0.58 mm
World Smallest
Optical Isolators

# World Smallest-Possible
# Free-Space Optical Isolators – Our Vision

## Conventional Approach

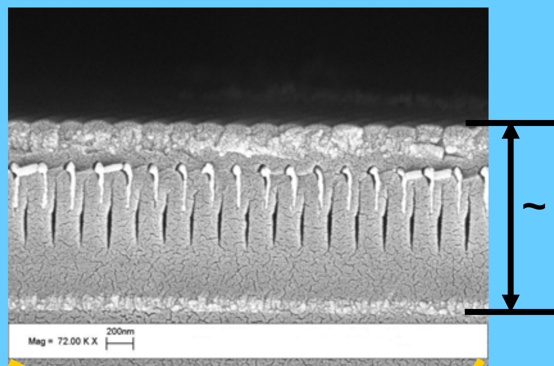


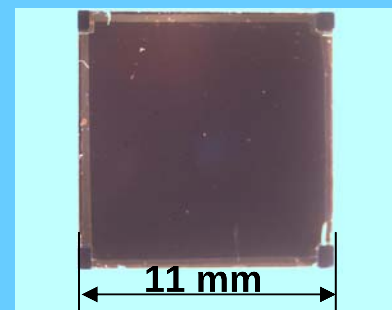

## Nano Monolithically Integrated Approach

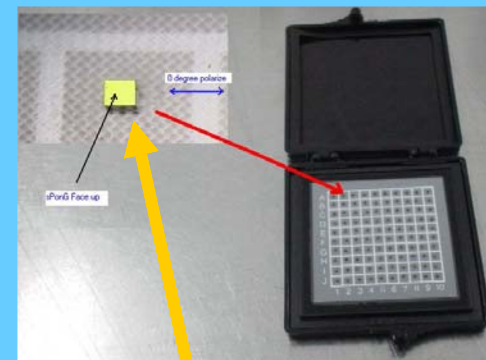


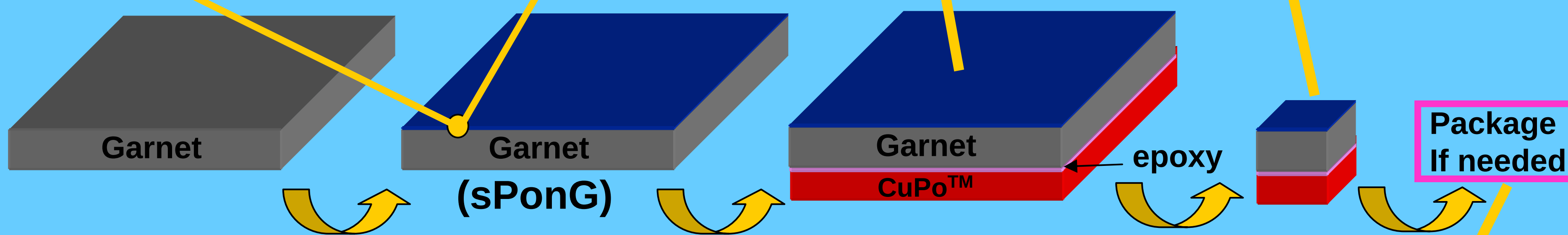

- Improve performance due to less interfaces, semiconductor process alignment accuracy
- Improve reliability (epoxy-free in the light pass, no curing caused stress release issue) and power handling capability
- Add system design freedom due to thinner/smaller isolator size
- Reduce cost (no alignment, bonding, and curing assembly steps)
- Significant cost reduction (can dice up to 4 times more isolators out of a same garnet wafer)
- Fabrication cost for nano-polarizer coating is low (< 10 cents/mm$^2$)
- Able to address double-stage isolators with all above advantages

# Free-space Optical Isolators
# – Current sPonG-isolator Process



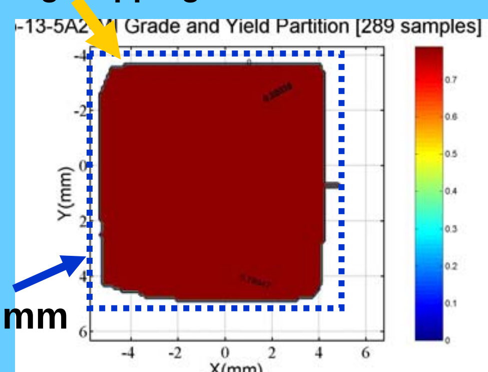





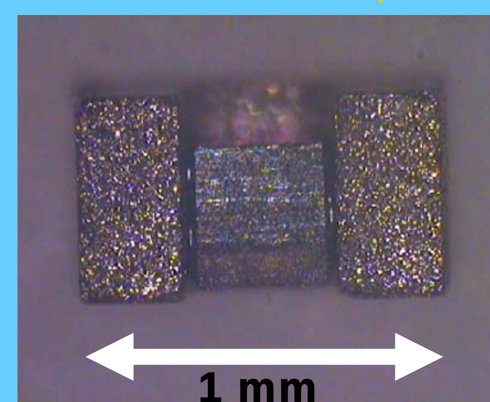

- Nano-optic design/simulation
  Garnet/ARC/nano-pol/ARC
  overall performance optimization
- Nanofabrication on garnet
  coatings/nanopatterning/etching/
  trench fill/coatings

- Epoxy/bonding with CuPo
- Testing/Mapping

- Dicing




Yield map



## *Performance of the isolators based on monolithically integrated semi-isolators*

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| Insertion loss (dB) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| S/N | 0 °C | | | 25 °C | | | 85 °C | | |
| | 1529 nm | 1550 nm | 1565 nm | 1529 nm | 1550 nm | 1565 nm | 1529 nm | 1550 nm | 1565 nm |
| Isolator #1 | 0.20 | 0.26 | 0.25 | 0.21 | 0.27 | 0.26 | 0.22 | 0.25 | 0.26 |
| Isolator #2 | 0.22 | 0.23 | 0.26 | 0.21 | 0.23 | 0.25 | 0.24 | 0.25 | 0.25 |
| Isolator #3 | 0.17 | 0.20 | 0.24 | 0.18 | 0.21 | 0.26 | 0.21 | 0.23 | 0.24 |

| Isolation (dB) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| S/N | 0 °C | | | 25 °C | | | 85 °C | | |
| | 1529 nm | 1550 nm | 1565 nm | 1529 nm | 1550 nm | 1565 nm | 1529 nm | 1550 nm | 1565 nm |
| Isolator #1 | 32 | 28 | 37 | 32 | 30 | 42 | 33 | 30 | 38 |
| Isolator #2 | 38 | 34 | 27 | 35 | 32 | 48 | 28 | 30 | 31 |
| Isolator #3 | 30 | 34 | 32 | 32 | 31 | 30 | 31 | 33 | 33 |

# Technology Uniqueness: Trim Retarder example

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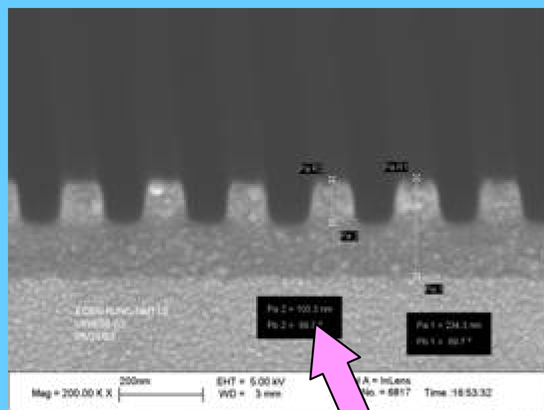
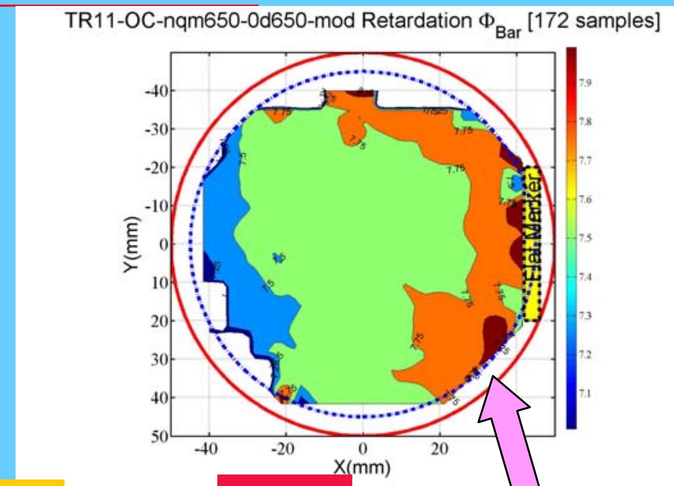
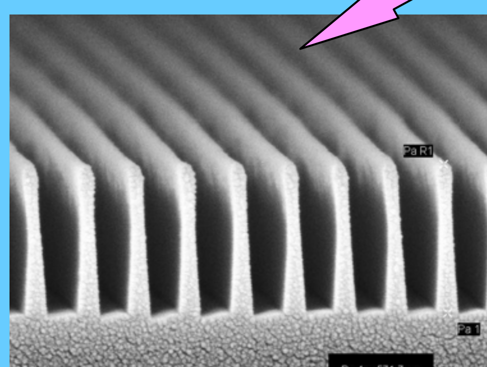
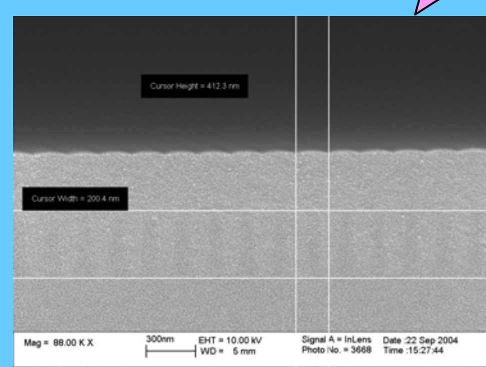
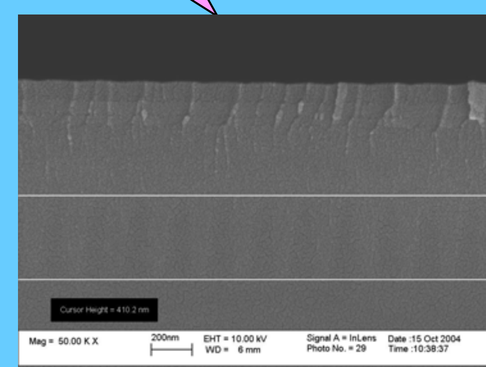




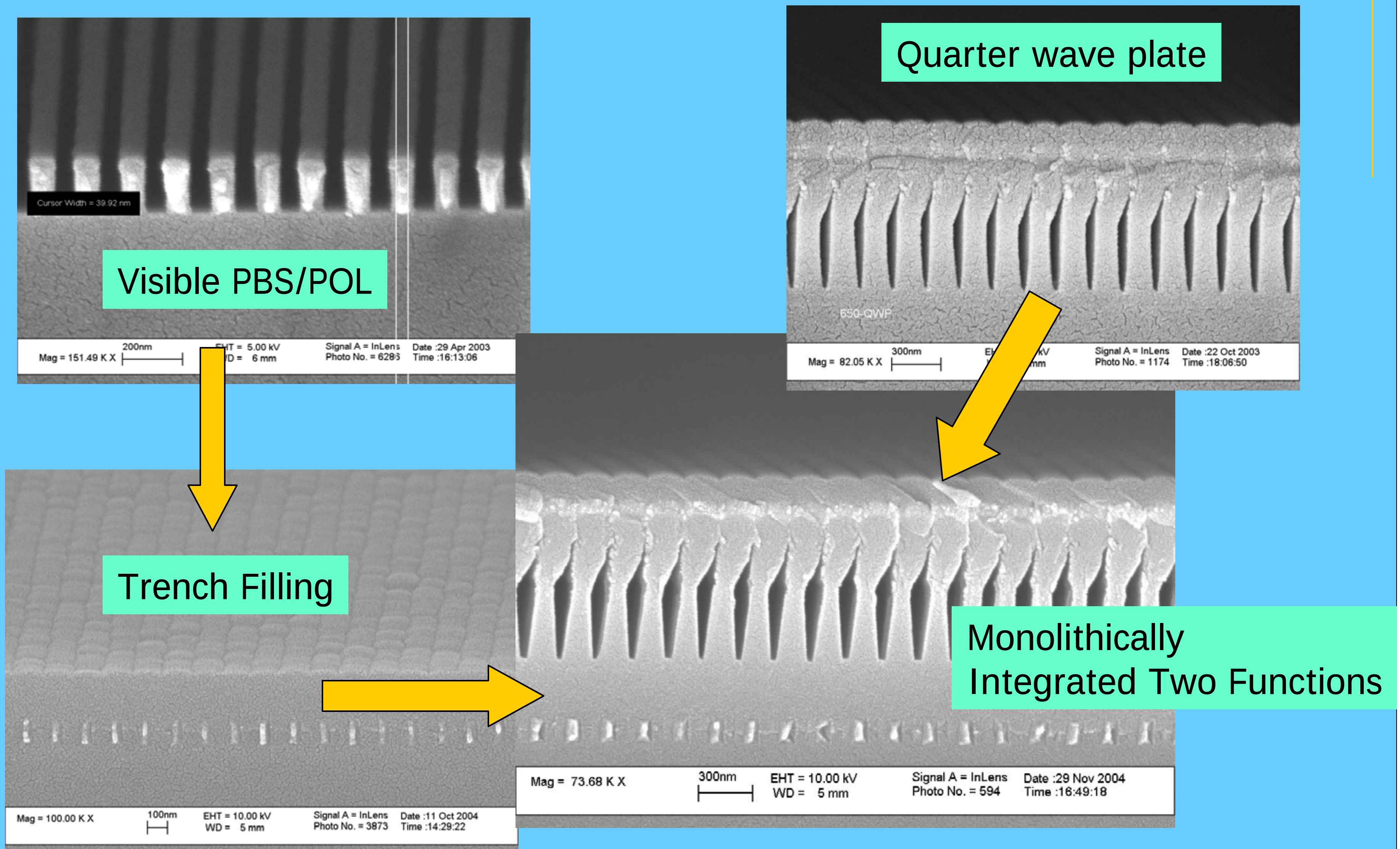

**patent** — **Design/ Simulation** → Substrate preparation → **Nano-pattern replication** (**patent**) → Semiconductor Nano-process (Know-How) → **Nanostructure Filling/ Nano-coating** (**patent**) → Testing/ Backend





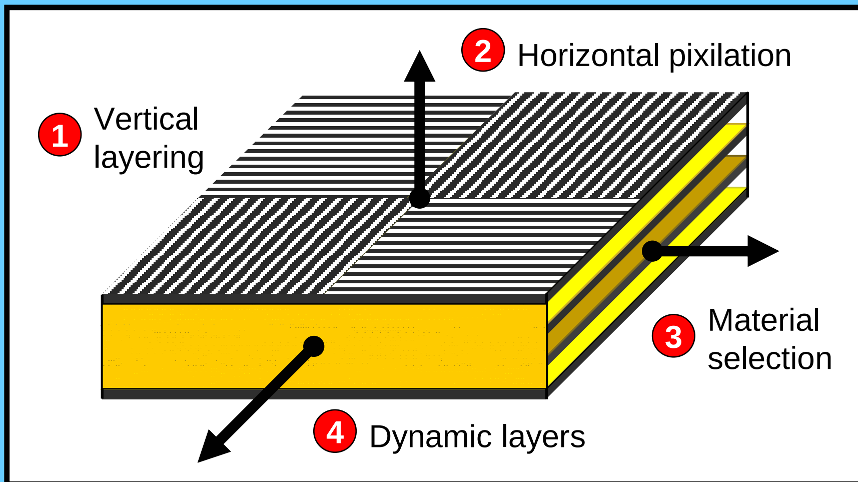


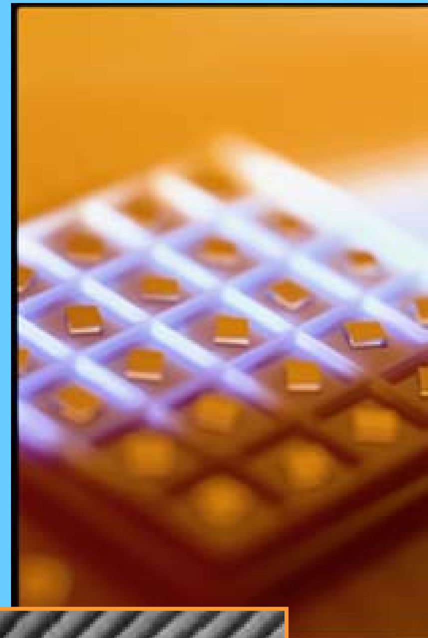
# Integration:
## Building Integrated Circuits



# 4 dimensional, integrated optics

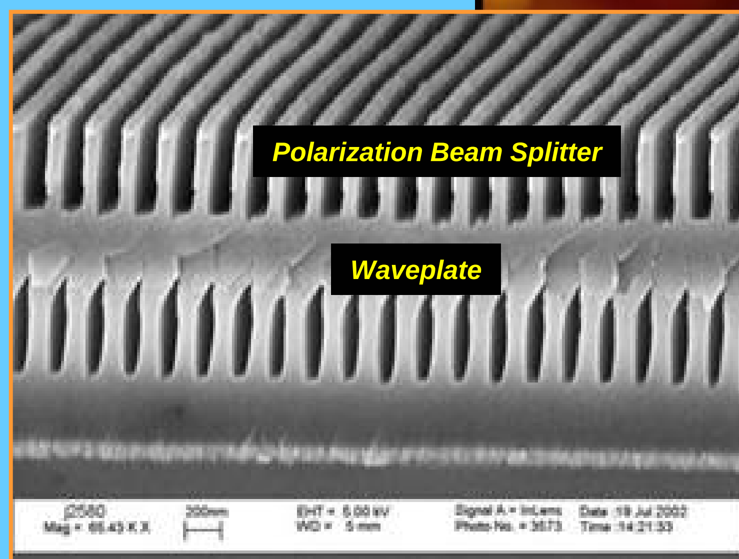
Nano-optic structures can be combined to create complex optical functions



**Monolithic integration**
- Pixel arrays
- Multi-layer structures

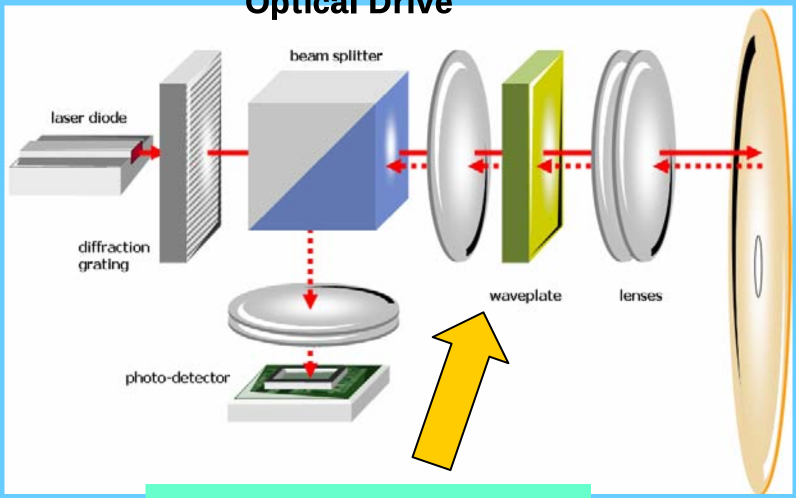
**Hybrid integration**
- Arbitrary substrates
- Dynamic substrates



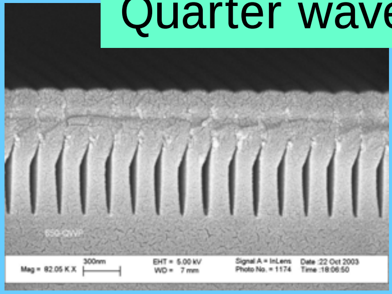
# Evolution path for nano-optic device functionality

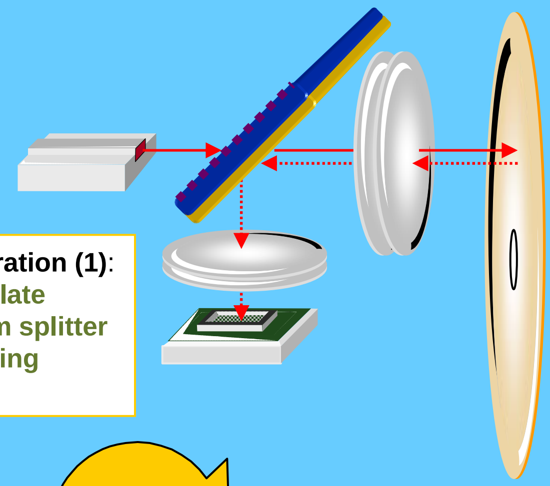
nanoopto
Improving performance through nano engineering

**Optical Drive**

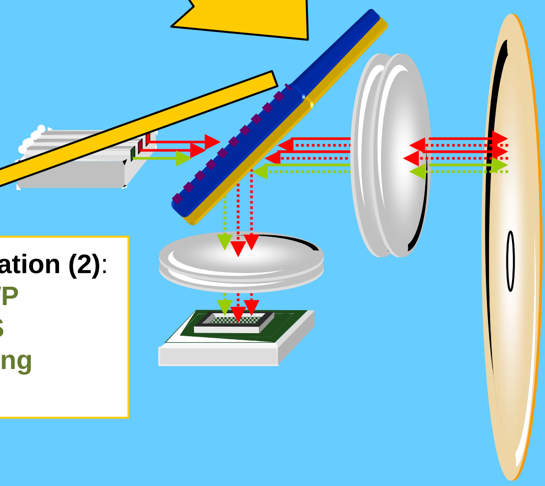


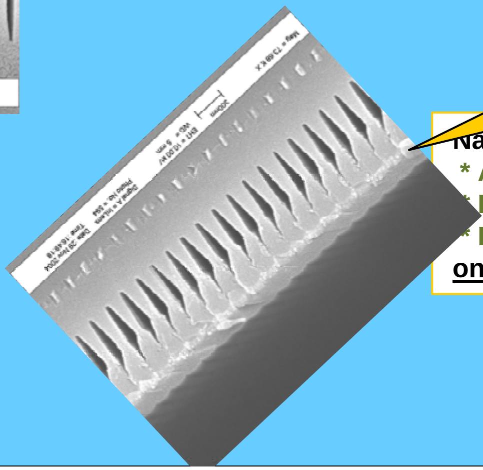

Quarter wave plate





**Nano-optic integration (1)**:
* Quarter wave plate
* Polarizing beam splitter
* Diffraction grating
**on a single chip**





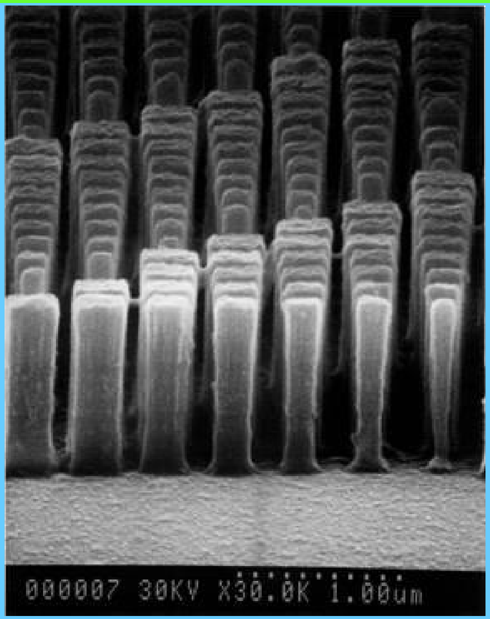
**Nano-optic integration (2)**:
* Achromatic QWP
* Broadband PBS
* Diffraction grating
**on a single chip**

# Long-Term Vision of NanoOpto Technology – (1)

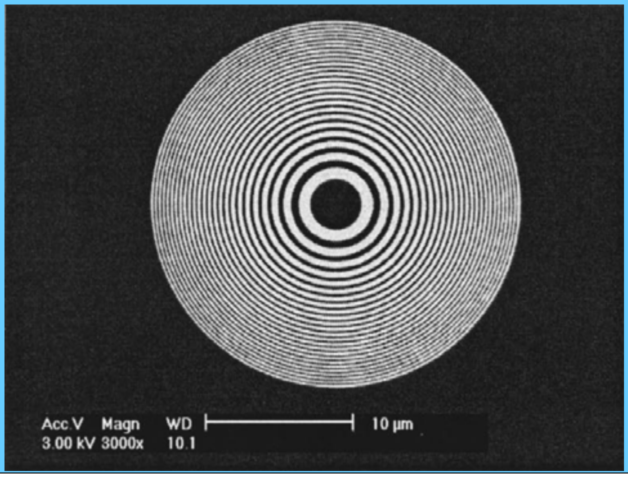
**Subwavelength and/or Nano-structured optical materials and applications**

- Generating new artificial optical materials and applications based on sub-wavelength/Nano- structure engineering and refractive index engineering – for applications covering from DUV to IR
- Control light propagation (Subwavelength/Nano-optic optical lenses)
- Control light confinement (Photonic crystals)
- Control light emission and detection (Active components)
- Tailoring the dielectric properties of materials for synthesizing artificial dielectrics and metals
- Tailoring the dispersion properties
- Controlling the polarization, color and antireflection properties of materials
- Exalting resonance phenomena for various applications like filtering or photodetection

**Subwavelength Optical Lens based on optical nano-engineering**



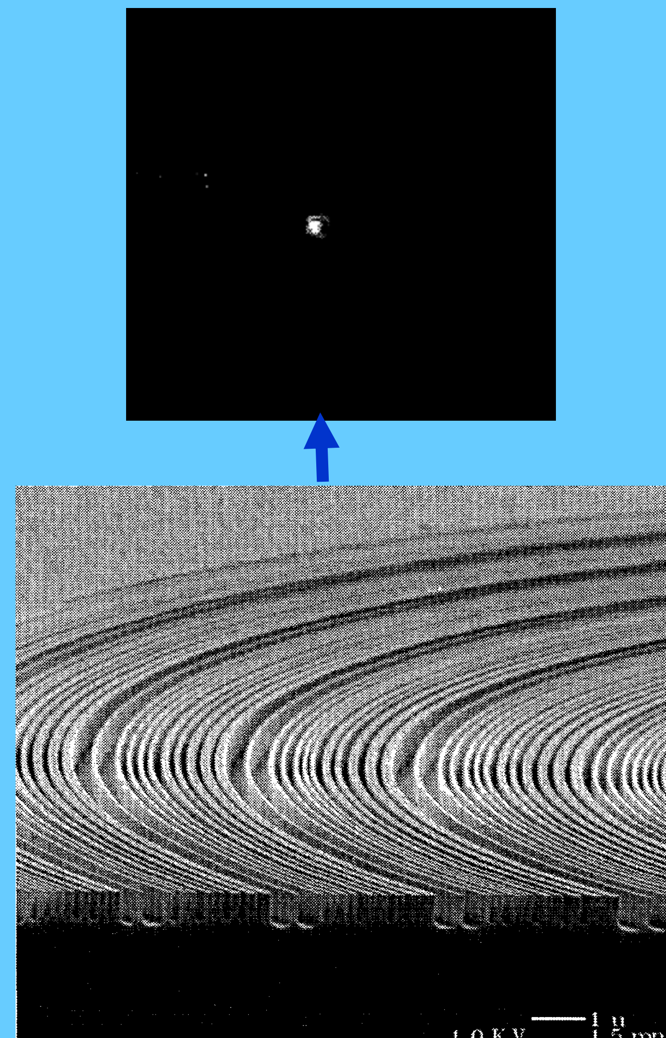

M. Li, J. Wang, Appl. Phys. Lett., 76, (2000).



# Long-Term Vision of NanoOpto Technology – (2)

## Integrated Optics based on Optical Nanostructures

- Integration on active optical substrates: integrated isolators
- Integrated on active optical devices: nano-optical polarization mirrors for laser/crystal facets
- Planar Lightwave Circuits based on nano-optical engineering
- Integration of polarizer, waveplate, filter, lens together
- Array optical devices based on nano-optical engineering

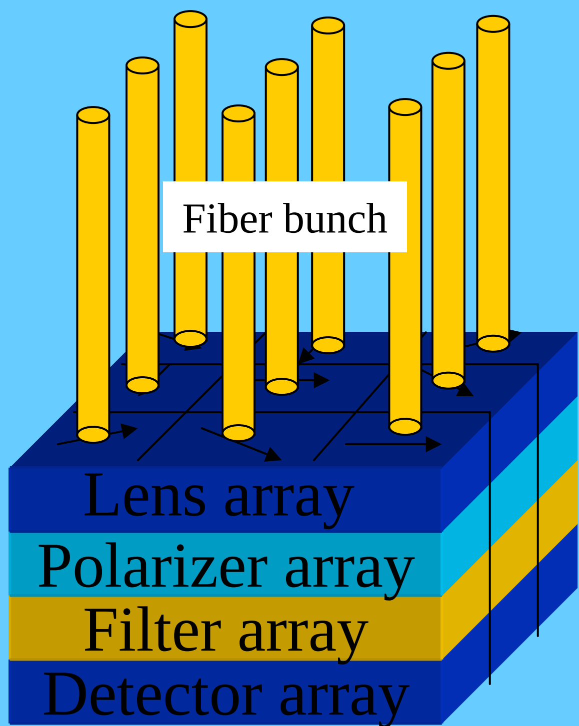


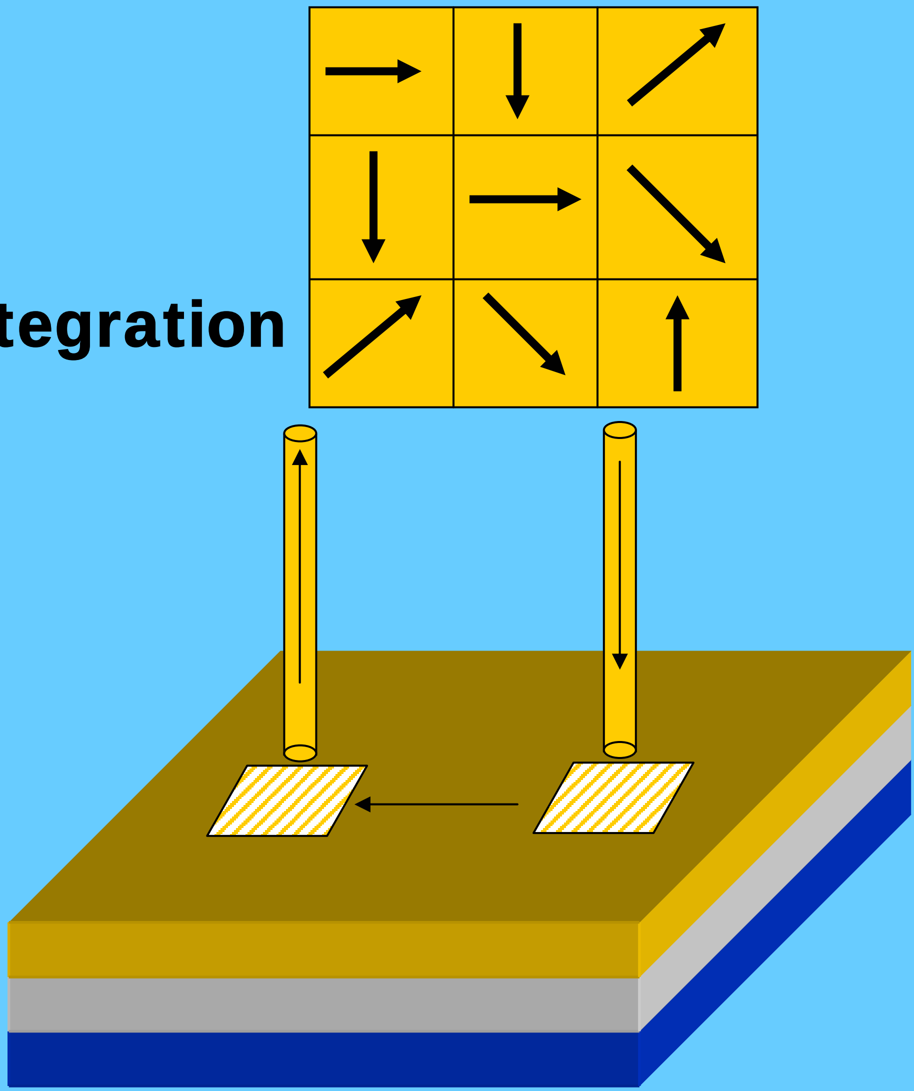
**Subwavelength Nano-optic Lens**

# Full Nano-optic Integration

## Lateral Integration

## 3-D integration

# Technology Leadership

- First commercialization of the Imprint Lithography technology
- First Imprint Lithography Production Line in the world
- Produced the world's largest acreage of optical nano-structures
- First successful commercialization of nano-structure based standalone optical components such as IR polarizers/PBS, quarter waveplates and trim retarders.
- First successful commercialization of nano-structure based integrated optical components
- First commercialization of immersed/embedded nanostructures for optical applications
- Built the world's strongest IP portfolio in nano-optic device fabrication, integration and applications

# Summary:
# Company information

nanoopto
Improving performance through nano engineering

- Nano-technology applied to integrating optics
- Shipping first products:
  - Telecom
  - Consumer optics
- ISO9001 certified nano-fabrication facilities
- C-round closed


1600 Cottontail Lane, Somerset, New Jersey, USA

**Founded Feb. 2001, $45M Capital to date**

MORGENTHALER VENTURES
U.S.TRUST PRIVATE EQUITY
DFJ
HARRIS & HARRIS GROUP, INC.
BESSEMER VENTURE PARTNERS
NEA NEW ENTERPRISE ASSOCIATES

**Experienced Leadership Team**

IBM
Lucent Technologies
SPECTRASWITCH
TRANSWITCH
AT&T
agere systems
AXSUN
Bank of America

# NanoOpto fabrication facility overview

- **Clean rooms and labs**
  - 3 clean room zones: Class 10, 100 and 1000
  - Zoning is based on process needs
  - Classic bay and chase layout
  - Additional lab space is used for testing and development

- **Fabrication capabilities:**
  - Nano-structured mold creation
  - End-to-end nano-pattern transfer wafer processing
  - Deposition and etching
  - Optical testing

- **NanoOpto is an ISO9001-2000 registered company**
  - Registration achieved in Dec. 2002

Wafer Fab and Labs

Clean Room 3