Future Technologies Division

MONA: Frame of Reference

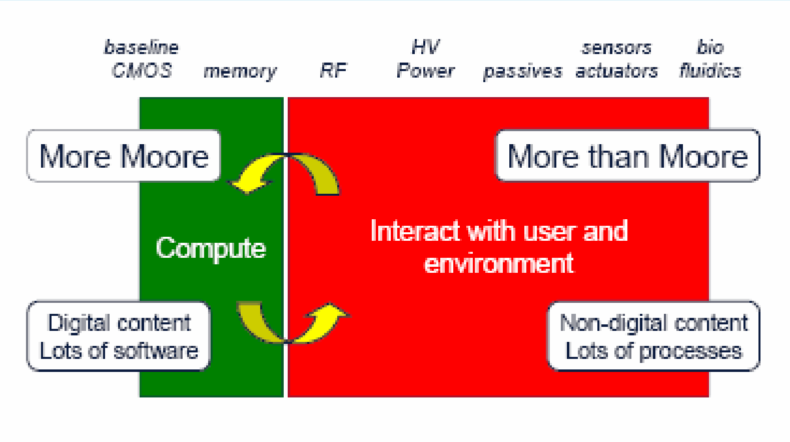
Strasbourg, April 7th 2006

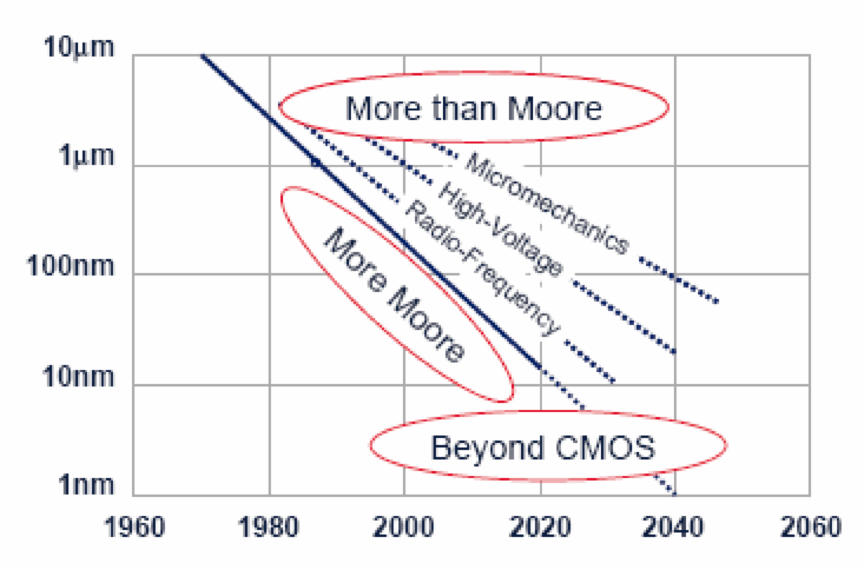
Dr. Dirk Holtmannspötter

Agenda

Merging Optics and Nanotechnologies

- **Definitions**
- Nanostructuring Technologies
  - Top-Down
  - Bottom-Up
- Nanophotonics
  - New Approaches
  - Photonic Devices
- Summary





Definition of Optics

Optics is the field of science and engineering

encompassing

the physical phenomena and technologies

associated with

the generation, transmission, manipulation, detection, and utilization

of light.

Definition of Nanotechnology

Nanotechnology is the technology concerned

with the

production, study and utilization

of

lateral structures, layers, molecular units,

inner boundary layers and surfaces

with

critical dimensions or production tolerances that extend from about 100 nanometers down to atomic orders of magnitude.

Definition of the "Merging" – Nano2Optics

Optics and Nanotechnologies merge,

where

lateral structures, layers, molecular units, inner boundary layers and surfaces with critical dimensions or production tolerances that extend from about 100 nanometers down to atomic orders of magnitude

are produced, studied and utilized for
the generation, transmission, manipulation, detection, and utilization of light.

~~Optics2Nano~~

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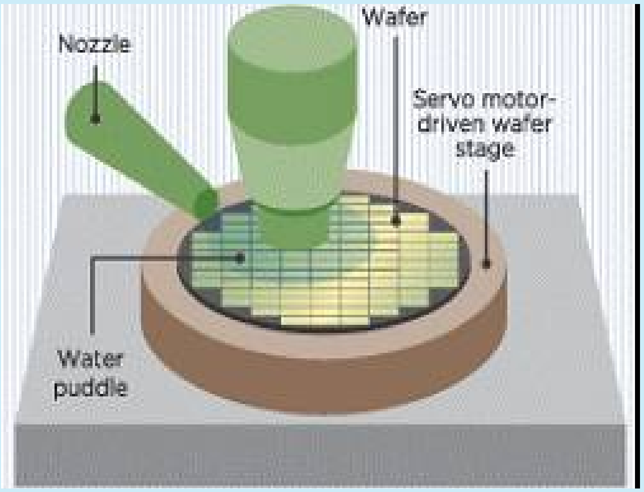
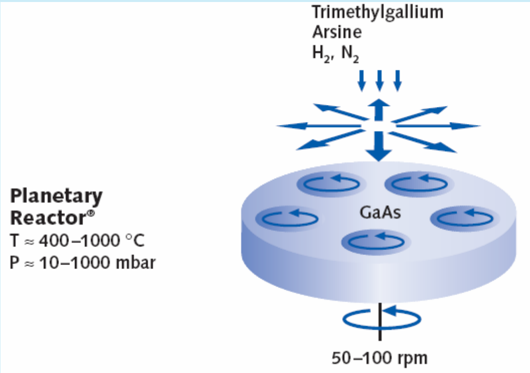
Nanostructuring Technologies

Top-Down

- Lithography (optical, EBL)
- Nanoimprint & Soft Lithography
- Etching





Bottom-Up

- Thin films
- Self Assembly
- Printing

Nanoimprint and Soft Lithography

Nanostructuring Technology	**Resolution**	**Throughput**	**Devices to be structured**	**Remarks Issues**	**Development Status**	**Release**
Soft lithography		(?) (300 mm)		- soft elastomeric stamp - step and repeat - pressure < 1bar - flexible multilayer soft stamp - IST SOUVENIR	1st generation tool	available (200k€)
Hot embossing	10 nm	150 (6”)		- hard stamp - thermoplast - full field exposure up to 250° up to 6-80 bar		
S-FIL	< 50 nm	5 wph (200 mm) 25 wph (300 mm)	- thin film heads - molec. electronics	- hard stamp - UV resist - transparent substrates - compatible with manufacturing in Si (Molec. Imprints)	2nd generation tool pre-production	available envis. 2007
Nanoplotter/dip-pen **Passive probe array**	60 nm (?) < 100 nm	 1 wph (4 inch)		system with 1.2 mio. pens	proof of concept demonstrator	

Self Assembly

- Self Assembled Polymers
- SAMs (Self Assembled Monolayers)
- Vapour Liquid Solid Process, Vapour Solid Process
- Templated Self Assembly
- Hybrid: Directed Assembly on Prepatterned Substrates
- Sol-Gel Processes

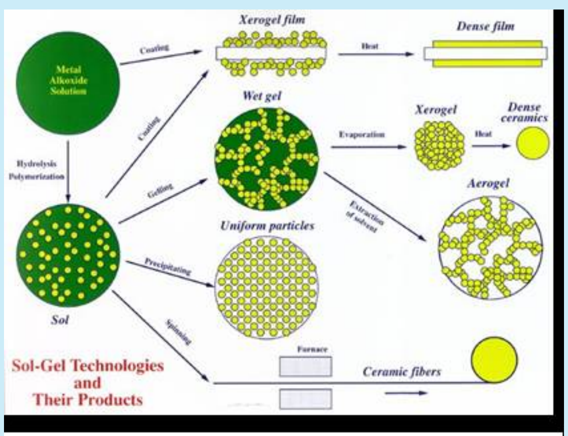


Fig 2.1.1 Diagram of Sol-Gel technologies; from [chemat].

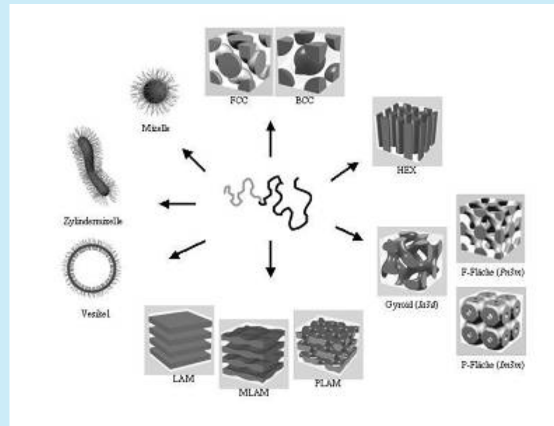


Fig 2.2.1 Self-assembled superstructures of AB-blockcopolymers source: [Förster, 2004].

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Printing Technologies

- Screen Printing
- Inkjet Printing
- Gravure and Flexographic Printing
- Roll-to-Roll Printing

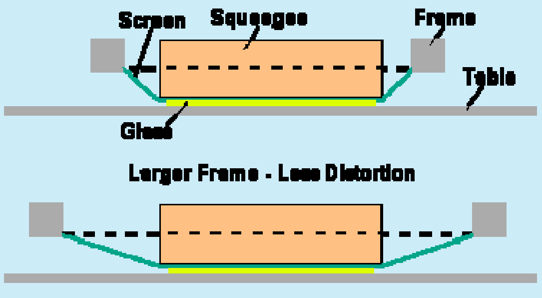

Fig.2.3. 1 **Schematic Illustration of screen printing, (source: [crystec]).**

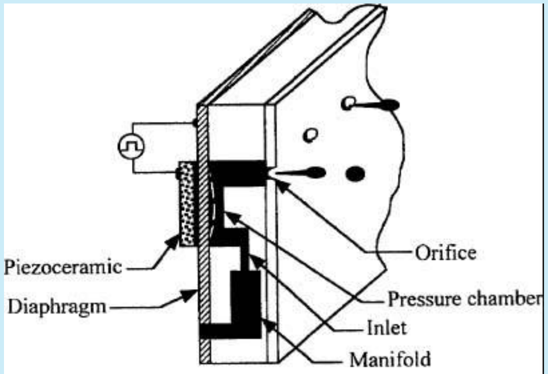

Fig.2.3. 1 Basic configuration of a piezoelectric printhead (source: [Le, 1998]).

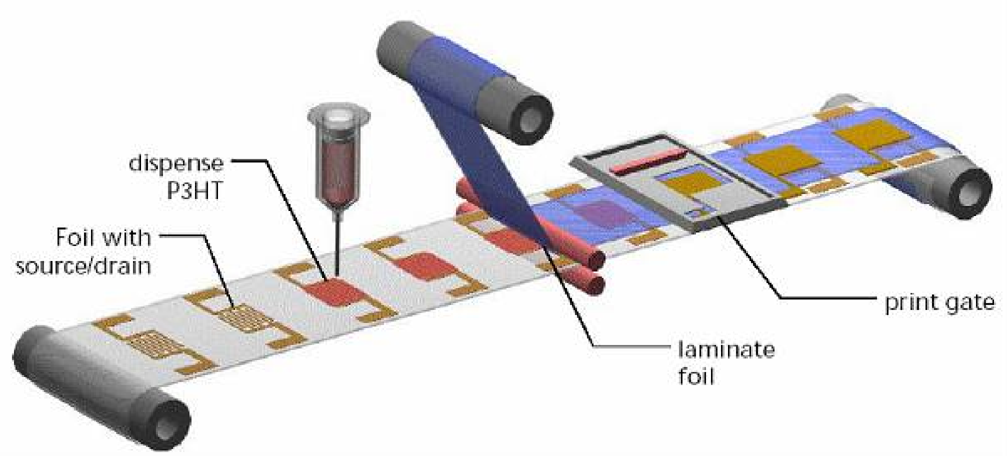

Fig.2.3. 1 Schematic illustration of the working principle of a roll-to-roll setup used for the fabrication of polymer-based transistors (source [FhG-IZM]).

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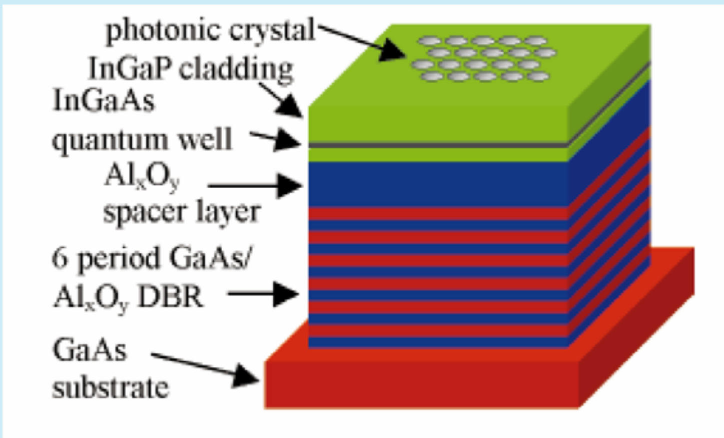
Nanophotonics

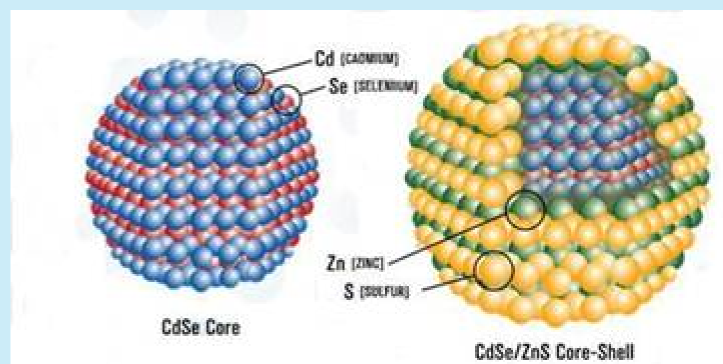


Photonic Devices

- Laser Diodes
- LEDs
- Sensors
- Displays
- Photovoltaics

New Nanophotonic Approaches

- Near-Field Optics
- Quantum-Confined Materials
- Plasmonics
- Photonic Crystals



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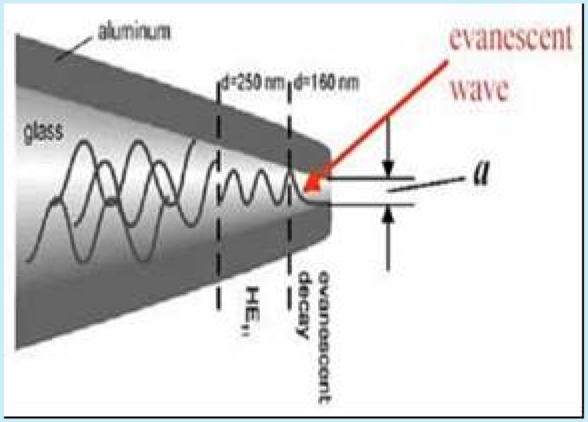
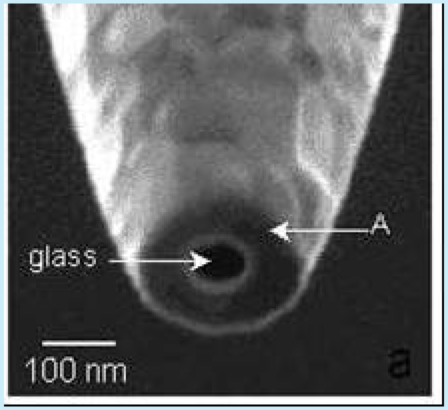
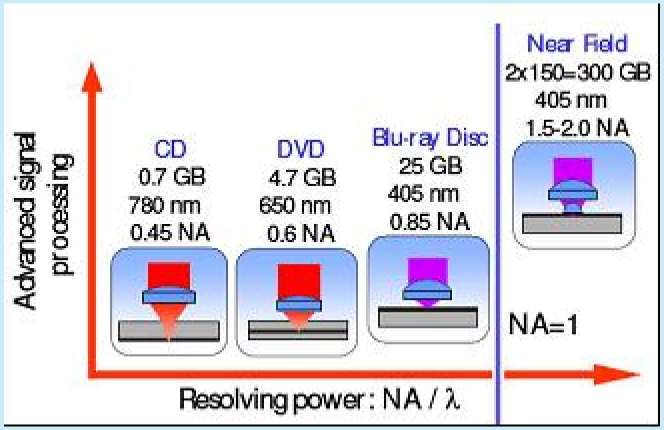
Near-Field Optics





SNOM

Optical Data Storage

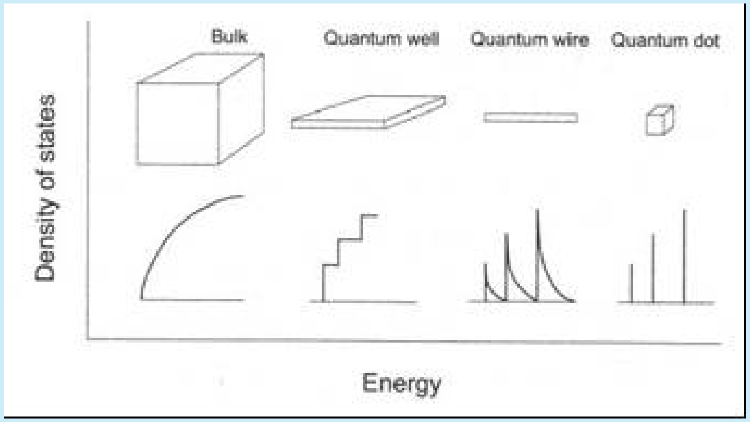


Quantum-Confined Materials

Quantum Wells – MBE, MOCVD

Quantum Wires – MBE, MOCVD + Nanolitho
– Self-organized Growth
– Catalyzed Growth

Quantum Dots – Heteroepitaxy
– Colloidal Synthesis



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Plasmonics

A plasmon is a collectively excited plasmawave of free electrons in metals where the electrons longitudinally oscillate against the ion-bodies of the material.

Surface plasmons are a subset of these 'eigen-modes' of the electrons, with the electronic oscillations being excited parallel to the surface of the metal. They are evanescent surface waves with the EM-field strength being enforced in the space above the metallic surface.

Resonant coupling of light into a nanostructure generating surface plasmon waves produces a large enhancement of the local electric field near the metal surface. Their field strength is increased by an order of magnitude compared to typical evanescent fields. Hence, a surface plasmon enhanced evanescent wave can more efficiently generate fluorescence and nonlinear optical processes that require higher intensities.

Discussion item: Negative Index of Refraction, Subwavelength Phenomena

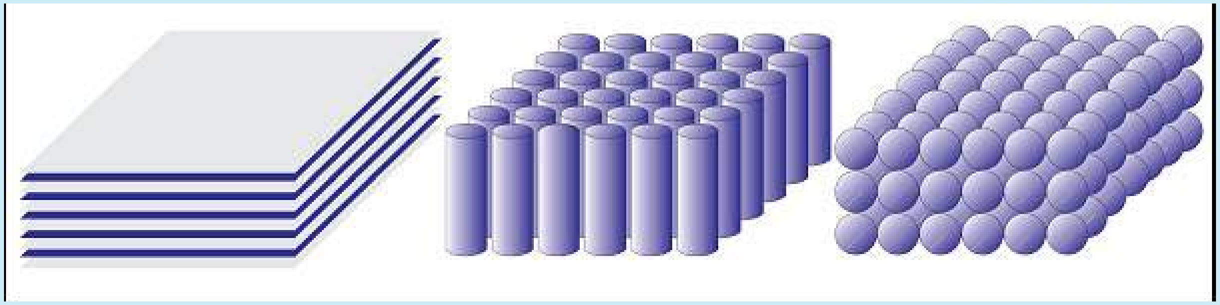
Photonic Crystals

The Semiconductor of Photonics: Defects = Dopants

Fabrication Methods

- Colloidal Self Assembly
- Sedimentation
- Cell Method
- Vertical Deposition
- 2-Photon Litho
- EBL
- Etching
- PVD-GLAD
- Holographic

Defect Fabrication is an Issue.



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Laser Diodes

Device	Nano-Component	Nanostructuring Technology	Development State	Remarks Issues	Chapter
Quantum well laser	quantum wells	MBE; MOCVD	fully commercial	ongoing further developments	4.2.1.1
Quantum cascade laser	quantum wells	MBE	partially "commercial"		4.2.1.4
Quantum dot laser	quantum dots	self-organized growth	research prototypes - getting closer to commercialisation	room temperature operation; dot diameters: to <5 -20 nm (pyramidal shape)	4.2.1.2
		colloidal synthesis	research prototypes	only optical excitation; highest acuracy and lowest cost in dot production	4.1.2.1 4.2.1.2
Quantum wire laser	quantum wires	nanoscale lithography	research prototypes	wire diameter: 43 nm	4.2.1.3
		self-organisation	research prototypes	pulsed lasing at 300 K	4.2.1.3
		selective growth	research prototypes	room temperature operation wire diameter: 43 nm	4.2.1.3
		chemical synthesis	research prototypes	only optical excitation; room temperature operation wire diameter: 70-100 nm wire length: 5 µm	4.2.1.3

LEDs

Device	Material Nano-Component	Nanostructuring Technology	Development State	Remarks Issues	Chapter
QD-Phosphor LED	Nanocrystals / quantum dots to replace the emitters or the phosphors CdSe, CdS, InP	colloidal synthesis	research/ development	- cost-effective deposition, - more stable; higher spectral purity, than organic materials; - emission wavelength depends on size of nanocrystal - CdSe (toxic) --> Focussing on InP-based nanocrystals - synthesis methods are scalable	4.2.2.4
Phosphor-Free SSL	- nanostructured UV/blue GaN based materials -nano-optical resonator concepts for planar resonant cavity LEDs	- optical confinement structures -advanced concepts of synthesizing quantum dots and quantum wires	research prototypes	DOE research program (2003-2006) to achieve >100 lm/W - enhance stimulated and spontaneous emission - enhance internal efficiency - develop efficient mesoscopic optical confinement structures in three dimensions	
OLEDs	small molecules	OVPD, OVPJ	production (small area devices)	- typically 15 lm/W - under laboratory conditions monochromatic OLED systems with 100 lm/W have been achieved -1000 hours lifetime	4.2.2.3 3.2.3.2
Nanowire LED	electron doped semiconductor nanowires (GaN; CdS, CdSe, InP) / hole doped silicon nanowires in crossed nanowire architecture	e.g. VLS (Vapour-Liquid-Solid) process -> directed self-assembly	research prototypes	-these nanoscale devices are synthesized by chemical means and subsequently integrated by assembly methods, rather than the established physical ones -> in the long run may promise cheaper, faster, more versatile fabrication of semiconductor devices, arrays, and related applications.	4.2.2.6 3.2.2
Nanorod LED	InGaN/GaN multi quantum well nanorod arrays	MO-Hydride VPE	concept	High brightness; high efficiency broad area LEDs	4.2.2.7
PC-LED	InGaP/InGaAs DBR = 1D Photonic crystal (PC)	MBE (PC EBL+RIE)	research prototypes	Erchak *et al.* demonstrated sixfold photoluminescence intensity increase utilizing a triangular lattice etched into the upper window layer of an InGaP/InGaAs LED emitting at 935 nm.	4.1.4

Sensors

Device	Nano-Component	Nanostructuring Technology	Development State	Remarks Issues	Chapter
Quantum well IR photodetector (QWIP)	quantum wells	MBE	commercial	- GaAs/AlGaAs - operation at T<200K	4.2.3.2
	multiple quantum wells	LP-MOCVD	research prototype	- InP substrate with 20 periods InGaAs/InP (detection range: 8-9µm) for LWIR and 20 periods InGaAs/InAlAs (detection range: 3-5µm) for MWIR - operation at T<77K	4.2.3.2
Optical antennas	antenna transducer element (size: 50 - 200 nm)	EBL	research prototype	- room temperature operation - detection wavelengths:mid IR (to visible) - FPA demonstrated	4.2.3.3
Thermal Sensor	CNT	CVD	research prototype	- power consumption in the µW range	4.2.3.5
UV Sensor	thin film of c-Si nanoparticles embedded in SiO_2	electrochemical etching or sputtering deposition	research	- UV induced photoluminescence - response time upon UV excitation: fs range	4.2.3
Polarization Sensor	InP quantum wires	EBL for electrical contacting thermal evaporation for contact electrodes	research	- large anisotropy in the photoluminescence intensity parallel and perpendicular to the nanowire axis	4.2.3.1
SPR Spectrometers	Surface Plasmons		commercial	- biological analyte detection by dielectric sensitivity of SPR	4.2.3.6

Displays

Device	Component	Manufacucturing Technology	Development Status	Remarks / Issues	Chapter
QD-OLEDS	Thin layer of inorganic nanocrystals (e.g. CdSe) sandwiched between organic layers, the latter serving for electron / hole transport	QD: Solution-based methods (colloid synthesis) plus self-assembly organic layers: spin coating		-Narrow emission spectrum of nanocrystals -stability of inorganic nanocrystals - hybrid organic/inorganic approach	4.1.2 3.2.1.5
CNT-FED	MWNT SWNT	cathodic arc deposition, CVD-based techniques, PECVD CVD (HiPCo) + screen-printing + self-assembly using CNT-powder particles mixed into a paste or an ink with adhesives	Proof-of-concept	- wide viewing angle - robust inorganic material issues: - vacuum sealing - phosphor efficiency for backlight applications; - no commercialized production for white phosphors for BLU; - uniformity and controllability of cathode emitter device depends on the uniformity of the cathode structure	4.2.4.4.1
SED	PdO conductive layer 30-50 nm carbon film	inkjet printing (PdO) electroforming creates sub-µ gaps in PdO conductance activation in presence of organic gas narrowing of gaps to create 4-6 nm gaps		- Low-cost fabrication techniques (large area displays) - contrast 8600:1 - no backlight unit - 60,000 hours of accelerated test, (emission dropped only by 10%) -power consumption reduced by more than 60% (30%) compared to plasma displays (LCD)	4.2.4.4.2
Nanochromic Display	nanostructured mesoporous metal oxide films (TiO_2) coated with a self-assembled monolayer of electrochromic viologens are deposited on an ITO-coated substrate	e.g. Sol-gel method (mesoporous metal oxide) + self-assembly of viologens	Production planned by [ntera]	-Large functional area due to porous metal oxide layer -switching speed milliseconds to seconds -memory capability -production can be realized at existing LCD-fabs, just by replacing some LCD-specific processes with ECD-specific processes (see [ntera], ch. 4.2.4.5)	3.2.1.4 3.2.2

Photovoltaics

Device	Component	Manufacucturing Technology	Power Efficiency	Development Status	Remarks	Chapter
All-inorganic solar cell with CdSe, CdTe NC	ITO/NC/Al	Colloidal synthesis spin coating + evaporative techniques for metal electrodes	2.9 %	lab	- rather cheap prod. techniques for functional layer - Stability of NCs	4.2.5.2
Dye sensitized solar cell (DSSC) (Grätzel)	TiO_2 + dye	- Sintering to produce highly porous TiO_2 (10-30 nm) - Wet chemical processes and screen printing to apply dyes	11 % (lab) 8% (prod. (?))	- prototypes - pilot-prod. in preparaton	-Sensitive to transform diffuse light -cost effective -Life-time: not yet clear; most likely a couple of years -Completely rechargeable cell: prog. 30 years of lifetime	4.2.5.2
QD-sensitized solar cell	TiO_2 + QD	Sintering and solution based techniques to deposit QD		concept	shown for: InP, CdSe, CdS, and PbS NCs	4.2.5.1
organic-solar cells		Solution based methods, screen printing	only around 1%		-cost-effective production methods -Inorganics with higher carrier mobilities, avoid recombination -Organic carrier mobilities < $10^{-4} cm^2 V^{-1} s^{-1}$	4.2.5.3
Hybrid Solar cell	CdSe nanorods (7nm*60 nm) +polymer Metal electrodes	Solution base dassembly; colloidal s Evaporation, sputtering	1.7 % (lab)	research		4.2.5.3

Further Issues

- Silicon Photonics
- Photonic Integration
- Optical Tele/Data-Comm, Optical Interconnects
- Slow Light Systems (EIT, ...)
- Metamaterials
- Nanomaterials for Packaging
- Single-Photon Systems (beyond a time horizon of 5 to 10 years)

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Summary – Nanocomponents vs. Devices

Comp. \ Device	Laser Diodes	LED	Sensors	Displays	Photovoltaics	Other
Near-Field Optics / SNOM	-	-	-	-	-	- Nanoanalytics - Nanolithography - Optical Data Storage
Quantum Wells	●●●	●●●	●●●	●	●	
Quantum Wires	●●	●	●	●●●	-	
Quantum Dots	●●	●●	●●●	●●	●●	- Optical Amplifier - Optical Switching - Optical Data Storage - Quantum Optics
Surface Plasmons	●	●	●●●	-	-	- Data Storage - Photonic Circuits
Photonic Crystals	●●	●●	●	-	-	- Mirrors and Interference Filters - Photonic Crystal Fibers

Summary – Nanostructuring vs. Devices

Nanofab. \ Device	Laser Diodes	LED	Sensors	Displays	Photovoltaics	Other
Optical Lithography	●	●	●●●	●	-	IC
EBL, IBL	-	-	-	-	-	Masks
Nanoimprint	?	?	?	-	-	
Soft Lithography	?	?	?	-	-	
MBE	●●	●●	●	-	●	
MOCVD	●●●	●●●	●●●	-	●	
Self Assembly	●	●	?	?	?	
Printing	?	?	?	●●	●●	

Up to discussion