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First Report		

Reliability of nanostructured materials and devices

Research partners:		Industry partners:	
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Abstract:
Reliable functionality is a basic requirement of any product. Reliability theory is generic in nature and can be applied to nanotechnology as well as to other fields. Failures of nanosystems can be treated as stochastic processes or by their physical failure mechanisms. In addition quantum statistics, thermal fluctuations and Heisenberg uncertainty relation have to be considered at the nanoscale to identify fundamental limitations and to estimate reliability, availability, minimum redundancy and maximum operation frequency for molecular, solid state and other devices.

Project aims:
The aim of this feasibility study is to identify relevant physical failure mechanisms and failure modes, to investigate modeling of reliability and failure rates and to determine quality parameters, testing procedures and requirements for analysis tools. Consulting with respect to reliability will be provided as a service to TOP NANO 21.

Reliability at the nanometer scale:
Reliability is one of the main properties of products in a safe and sustainable environment in addition to performance, costs and ecological impact. High reliability is often stressed as an argument for projects in nanotechnology. Despite these claims only little work has actually been done in the field of reliability in nanotechnology in clear contrast to microelectronics, which is now extending its reliability modeling to nanoscaled semiconductor circuits. An example is the modeling of time to breakdown of gate oxides with a thickness of 1 to 5 nm due to charge trapping or lattice defects. Classical reliability models may be insufficient due to quantum effects and thermal and defect diffusion processes. Reliability estimates of molecular, solid-state or any other system with nanosized functional elements have to consider thermal fluctuations, quantum statistics and Heisenberg uncertainty relation resulting in contradicting requirements for minimum energy level separation of states, operation frequency and packing density (1). For a complex system with a large number of individually functional unit cells their reliability must be very high for the system to ever be operational or redundancies have to be built in which should be more efficient than just operating larger ensembles. It has been exemplified that at least 10^4 molecules may be required to store a single bit of information reliably (2). To maintain redundant information efficiently in a system where the phase of quantum states has to be considered is an unsolved problem, although procedures have been proposed to copy information without decoherence of the wave function as required for redundant storage in quantum computing (3).

Failure analysis:
Failures are caused by mechanisms, which can be expected to be an order of magnitude smaller than the functional elements themselves. Therefore failure analysis of today's state of the art microelectronics and MEMS devices already require nanotechnological methods. EMPA has supplemented its already broad micro-analytical capabilities (SEM, ESEM, AFM, STM, etc.) with focused-ion-beam (FIB) and transmission electron microscopy (TEM) to cover future requirements including those of some TOPNANO 21 projects.

Reliability and TOPNANO 21 projects:
Many TOPNANO 21 projects are still in an exploration phase defining functionality of new nanostructures. It seems difficult to apply reliability studies in an early stage, but ignoring fundamental reliability limitations may lead to a dead end. Reliability and failure mechanisms depend on the specific nanodevice; we can give here general considerations only.
In order to estimate the reliability of a unit with statistical or physical methods, its function, load and working environment have to be defined. Then one has to analyze the failure causes and failure modes either from field failures or accelerated stress testing. Failures depend on both used materials and unit design. For reliability modeling a deep understanding of the physical principles of the units is required. Absolute estimates of reliability of micro and macro systems based on physical modeling only most often do not provide adequate results, but due to reduced complexity of nanosystems better results can be expected allowing reliability estimates before actually producing any device.
Table 1 gives three examples of nanodevices and compares them with microelectronics with respect to reliability. It is evident that many reliability specific features are not well known or are missing.

Table 1: Reliability Aspects of Selected Nanodevices

	Microelectronics (CMOS)	Coatings	Carbon Nanotubes	Nanosensors (Bio- and Chemo-Sensors)
Dimensions	0.15μm, oxide: <4nm	nm/μm composit.	dia. 0.6-1.8nm (sw) – 20nm (mwl)	<μm^2, 5-20nm
Materials and Properties	Si, SiO_2, Al, Cu, B, P	e.g. TiN/Si_3N_4 TiN/MoS_2	1.33-1.4g/cm^3 E=2*10^{9}Pa, j=10$^{11-12}$A/m^2 temp. stab. 750°C air, heat trans. 6kW/m/K RT	bio- and synthetic supra-molecules, switchable membranes, intercalation compounds, sieves, catalysts
Device Concept and Function	electrical switching >2 GHz, at 1.2-3.3V, 50 million transistors, km wiring, 6-8 metal layers, 1000s I/O	mech. protective layer	field electron emitters, field emission at 1-3 V/μm	DNA/RNA chips, switchable molecular functions, molecular traps, drug delivery, biodetection
Structuring and Synthesis	top down photo-lithography, chemical etching, diffusion, ion implant.	(PA)-CVD, sputtering	bottom-up, CVD laser ablation, arc discharge	bottom-up, dipcoating, self-assembly, cov. binding, ink-jet printing, polymerization
State of Technology	mature production	mature production	principles demonstrated mass fabrication not yet sho0. wn	emerging understan-ding of 3D structure; gas, DNA, molecule sensors; fluorescent / magnetic labels
Failure and Degradation Mechanisms	latch-up, ESD, EOS, TDDB	chemicals HCl, SiH_4, H_2, delamination, pin-holes	high j, temperature, coupling between electrons and vibration leads to energy dissipation, tube distribution leads to inhomogeneous field emission, oxygen may change electrical properties, non-perfect growth in length, orientation, spatial distribution	UV light, temperature, chemical agents, selectivity, sensitivity, photobleaching, repeated sampling
Symptoms, local effects	short, interrupt, leakage current	delamination, homogeneity	local field enhancement; electronic properties depend on diameter and chirality, conductivity by low dimensional qm-effects	cross-sensitivity
Observ. and Local. Meth.	SEM, EMI, FIB, TEM E-Beam, Obirch....	Electr. micros-copy, AFM, FIB	scanning anode field emission, AFM and SPM methods, FIB	fluorescent techniques, SNOM, SPM
Reliability Remarks	10-200 FIT test acceleration factor up to 1000	many functional coatings with good reliability	longer lifetime than metal microtips claimed (chemical inertness, lower operation voltage due to higher local field enhancement), crit. manipulation	storage problems, synthesis side reactions, radiation, acc. tests difficult

Further steps:
Failure mechanisms will be investigated and failure rates estimated for representative nanodevices and systems. To select these examples requirements of TOPNANO 21 projects will be considered. Participants of TOPNANO 21 who are interested in reliability and lifetime of functional nanodevices under investigation are invited to contact one of the authors at EMPA. Reliability services provided are consulting, modeling of failure mechanisms, failure rate and lifetime, failure analysis, and accelerated aging. Extended work would be outside this feasibility study and require a request to Top Nano 21 for funding.
A Nanoworld Reliability Network registered with the European Commission will be consolidated and extended.

References:

(1) Technology Roadmap for Nanoelectronics. European Commission, 2001, p. 18.
(2) R. R. Birge, A.F. Lawrence, J.R. Tallent. Quantum effects, thermal statistics and reliability of nanoscale molecular and semiconductor devices. Nanotechnology 2 (1991) p. 73-87.
(3) John Preskill. Battling decoherence: The fault-tolerant quantum computer. Physics Today, June 1999, p. 24-30

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