

MEMS for

QUALITY *of Life*

Introduction to a collection of articles by MEMS Industry Group (MIG) members

MEMS technology is a great match for new biomedical applications that improve quality of life (QoL) in a variety of ways. Providing intelligent sensing and actuation — which can be combined with electronics processing 'muscle' like ASICs, microprocessors and even DSPs — MEMS enables a high degree of interactivity with the environment. MEMS packs this intelligence into a small footprint, making it the ideal companion for resource-constrained applications.

Today MEMS is helping engineers to accomplish what we never thought possible. We asked some top innovators in biomedicine to describe how they use MEMS in life-enhancing and even life-saving QoL applications. In his article, "The MEMS Revolution in Biomedicine," Dr. Jeffrey Borenstein of Draper Laboratory explores the BioMEMS' connection to some amazing developments in tissue engineering, organ-assist devices and drug delivery systems. Donna Sandfox of Omron offers an inside look at SynCardia's bridge-to-transplant Total Artificial Heart in "MEMS Technology in Real Life: A Critical Part of the Total Artificial Heart."



**Karen Lightman,
Managing
Director, MEMS
Industry Group**

*MEMS Industry
Group is the trade
association
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across global
markets.*

Dr. Dan Siewiorek of Carnegie Mellon University's Quality of Life Technology Center gives us a fascinating glimpse of some QoL Technologies (QoLT's) designed to allow seniors to live healthier, more independent lives in "Making Sense of our Aging World."

And we didn't stop there. Dr. Randy Goodall of NanoMedical Systems and Michael Lee of SVTC turn the concept of traditional pharmaceuticals on its head with their article on Personalised Molecular Drug-delivery Systems titled "Quality of Life from MEMS."

We are also enormously pleased to have Analog Devices' contribution, "Inertial MEMS, from Life-Enhancing to Life-Saving," by Bob Scannell, which gives an excellent overview of what can be "measured, monitored and ensured" with MEMS-enabling medical devices.

If the MEMS-QoL connection has you in its thrall — as it does me — I hope that you will consider joining a number of our authors and me at the MEMS Industry Group Symposia, "Quality of Life and Medical Applications" at Microtech 2011 in Boston, 14th June, 2011. For more information, please visit the MEMS Industry Group website: <http://www.memsindustrygroup.org/QoL>

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Bob Scannell, Business Development Manager, Inertial MEMS Products, Analog Devices

Inertial MEMS, from Life-Enhancing to Life-Saving

Motion is both integral and essential to life. Those of us who are mobile are in seemingly perpetual motion, and for those who are immobile, mechanical aids of some form may be required to assist in providing motion. It is not difficult to imagine then how an inertial sensor capable of measuring this motion could become as valuable in delivering useful information about ourselves as an audio (microphone) or optical (camera) sensor is today.

When it comes to Quality of Life (QoL) discussions related to MEMS, it may be useful to define varying degrees or stages: from Measuring to Enhancing to Ensuring. As with audio and optical sensing, it is easy to identify applications where inertial sensors can measure, capture or gauge an individual's output/health. For instance, a pedometer uses an accelerometer to detect steps and provide a measurement of fitness activity. Motion detectors embedded in a prosthesis for better balance/control can enhance the mobility of the disabled, and accelerometers detecting upright vs prostrate positioning can be used for life-saving patient monitoring.

There is a range of technical challenges and level of complexity in motion sensors, across the QoL opportunities for Measuring vs Enhancing vs Ensuring.

While the success of inertial MEMS sensors within the automotive and consumer markets has brought about rapid advances in sensor performance along some metrics, there is still a substantial difference in performance requirements between those existing applications and the still

Impact on Quality of Life				
Sensor Parameter	Measuring	Enhancing		Ensuring
		Body-Worn	Surgical or Diagnostic	
Power	H	H	M	H
Size	M	H	M	H
Reliability	L	M	H	H
Environmental Robustness	M	M	H	H
Performance	L	H	H	H
Performance Drift	L	H	M	H

Table 1. Relative Specification Comparison Across the QoL Application Spectrum. Level of Complexity, Performance Challenge: L: low-end; M: mid-range; H: high-end, most challenging.

emerging needs of medical Quality of Life. Examining the broader needs across applications requires a comparison of Power, Size, Reliability, Environmental Robustness, Performance, and Performance Drift. Power and Size are the two of these specifications which have already been pushed to extreme levels by consumer applications. Reliability and Environmental Robustness, having been required at high levels in automotive sensors, are close behind.

QoL Measurement applications, such as activity monitors, benefit from low-power, small-size sensors. They also require a high level of environmental robustness in order to distinguish actual desired movement from other random influences. QoL Enhancement tools can be separated into body-worn devices, such as prostheses, and surgical or diagnostic devices, such as robotic surgery tools or portable ultrasound devices. In either case, the increased level of active control vs passive

monitoring of measurement devices necessitates increases in performance and reliability as well.

To address QoL Ensurance, including micro remote surgery and other life-critical monitors, a combination of high performance, very low drift over time, and minimal sensitivity to environmental influences is required.

Table 1 establishes some relative figures of merit comparing the complexity of various types of QoL applications across broad specification factors. Even for the relatively lower-level requirement found in Measurement devices, the combination of very low power and small size, along with the ability to reject temperature/shock/vibration influences, sets the needs of these applications apart from the simplest of consumer-driven sensor needs.

Beyond the characteristics of an individual sensor, measuring linear motion (single-axis accelerometer) or angular motion (single-axis

gyroscope), for example, there are relatively few real-life scenarios in which motion is limited to (or discernible by) a single sensor type, or single axis. To capture the most precise representation of motion, or to allow use under unrestricted conditions (mounting position or range-of-motion), it is advantageous to intelligently merge multiple sensors and to accurately align the sensors to the application reference frame. So, in addition to the basic transducer element, the mechanical and sensor/signal-processing requirements also vary widely, and increase in complexity as we move from Measure to Enhance to Ensure.

The use of inertial sensors in the operating room for more accurate alignment of artificial joints (knee or hip) to a patient's unique anatomical structure is particularly interesting. This QoL-Enhancing application aims to improve joint alignment to less than a one-degree error from the patient's natural alignment axis compared to what is often a three-degree or larger error today with purely mechanical alignment approaches. This has the potential of offering less invasive and shorter surgery time, as well as substantially more post-operative comfort, and longer-lasting joint replacements.

Bob Scannell is a Business Development Manager for Inertial MEMS Products at Analog Devices. He has been with ADI for more than 15 years in various technical marketing and business development functions, ranging from Sensors to DSP to Wireless, and previously worked at Rockwell International in both design and marketing.

Dr. Daniel P. Siewiorek, Buhl University Professor of Electrical and Computer Engineering and Computer Science at Carnegie Mellon University — Quality of Life Technology Center

Making Sense of our Aging World

An AgeWave is unavoidable, and, the statistics are sobering: in the US 76 million 'baby boomers' are starting to reach retirement. As people age, however, their likelihood of developing serious health conditions increases. The US Centers for Disease Control and Prevention report that 1.5 million currently reside in skilled nursing homes; it is probable that the influx of elders will result in major shortages of caregivers and assisted care facilities. And the trend is global: worldwide the number of people aged 65 and older is expected to more than double from 357 million in 1990 to 761 million by 2025.

How will we care for all these people? And what sorts of lives will they lead?

We know that real quality of life is directly tied to independence. We like to do what we can do for ourselves. Intelligent systems can help to maintain or enhance one's ability to live independently longer, but such systems must strike a careful balance. Quality of Life Technologies (QoLTs) are intelligent systems that address what a person wants to do, minus what he or she can do. These systems provide just enough intelligence to adapt to an individual's unique needs, but not more assistance or automation than that person desires.

In essence, QoLTs must enhance rather than simply replace natural human capabilities. For this reason, QoLT systems must often be person-, context-, or environment-aware. They must be capable of responding quickly to changing conditions and circumstances. Sensor technologies are therefore integral to the QoLT approach.

MEMS provides a foundation for continual awareness, recognition and learning required for efficient and effective QoLT design.

Current QoLT research and development provides several examples of how MEMS technology can improve QoL. Unless otherwise noted, the examples below are currently in research and development at the Quality of Life Technology Center — an engineering research centre jointly run by Carnegie Mellon University and the University of Pittsburgh.

Let's explore how MEMS is enabling QoLT enhancements by mind, body and community:

For Mind: QoLT Systems that Interact with a Person Cognitively

While tracking technologies are now prevalent, they are often reactionary, inflexible and context-insensitive. In contrast, 'virtual coach' devices facilitate a person's functional needs by monitoring activities; providing appropriate support as circumstances change; and giving timely feedback to users and clinicians. Virtual coaches can be used to prompt the steps and order in which to perform a specific task or to provide clinical guidance on therapy or rehabilitation routines. One goal is to help people understand their behaviours and motivate them to take action towards positive change.

The MemExerciser is a good example. This device enables people to engage in 'reminiscence therapy' for important events. The system captures the user's experience with wearable sensors (a camera, audio recorder and GPS logger) then uses content and context to analyse the lifelog. Caregivers use the best

content to present photos, sounds and annotations back to the user. Cognitive recall among people with memory impairments has been shown to improve with the use of the MemExerciser.

For Body: Wearable QoLT Devices and Mobility Solutions Interface with Humans Directly

Wearable sensors are also surfacing in commercial markets. Devices like BodyMedia's FIT armband are equipped to track caloric intake, monitor sleep quality, detect mood changes or alert individuals to physical stress thresholds.

VibeAttire introduces a product with mainstream appeal. Users can plug an iPod or other audio player into a sensor-lined vest that vibrates to the music. While anyone can enjoy a new musical experience with VibeAttire, the product's sensory substitution-based approach is especially important for people with hearing impairments who may feel and respond to music for the first time.

For Community: Ubiquitous Sensing of the Environment and Context in Which One Lives

QoLTs can be employed in group home settings to minimise some of the burden on our healthcare system and caregivers. A communal health



Figure: A communal health kiosk lets seniors monitor their health and vital functions on a regular basis — without a doctor visit.

kiosk enables senior citizens to track their health and vital functions on a regular basis without doctor visits. The customisable system includes an integrated, multi-sensor system for physical, physiological, cognitive and behavioural monitoring of a

patient's total well-

being. As a telehealth solution, a remote clinician arranges for appropriate tests to be taken at the kiosk; then the results and compliance reports are recorded and returned to clinicians electronically. Tests span blood pressure, blood-oxygen levels, handgrip, weight, hearing, visual acuity and stress levels. The kiosk displays historical data so that patients can review their progress regularly with the help of carefully designed visualisations.

These QoLT systems help people to remain active, productive and employable well into their golden years. They also instill greater confidence, safety and mobility across a wide range of environments.

The QoL Technology Center is one of five Engineering Research Centers in biotechnology and healthcare funded by the National Science Foundation. The Center addresses activities of everyday living by prototyping personal assistive robots, cognitive and behavioural coaches, human awareness and driver assistance technologies.

www.qolt.org

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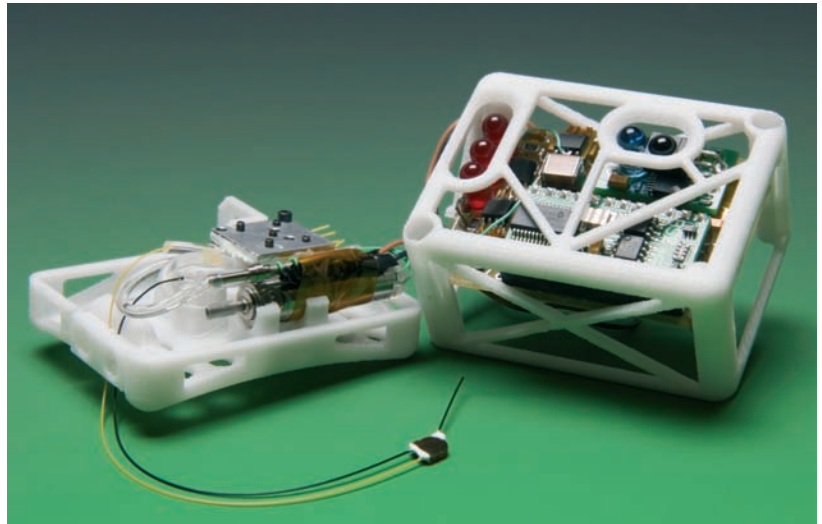
The MEMS Revolution in Biomedicine

The urgent need for solutions that help patients suffering from tissue loss and organ failure is leading to revolutionary developments in tissue engineering, organ-assist devices and drug delivery systems. While resolving the many challenges related to fundamental biological problems linked to cell sourcing and cell behaviour continues to be a major priority in the field, we recognise the emergence of engineering tools as another critical element of devices and systems aimed at augmenting or replacing organ function.

Micro fabrication and BioMEMS (BioMicroElectroMechanical Systems) -based tools and technologies are enabling researchers to replicate the structure of tissues and organs in engineered constructs for applications in regenerative medicine. These advances mean that new medical technologies will soon be available for implantable and smart drug delivery systems, improved in vitro assays for drug development and testing, engineered tissue.

Many recent advances in regenerative medicine stem from the emergence of BioMEMS fabrication technologies such as soft lithography, micro moulding, assembly of 3D structures and biodegradable micro fluidics. Most of these technologies were originally developed for lab-on-a-chip applications, but they are now being applied to next-generation medical devices for wearable and implantable uses. BioMEMS devices have evolved from early silicon-based laboratory devices to a broad class of polymer-based structures and

Figure: Draper is developing an implantable device that can deliver drugs in a controlled and timed manner to the inner ear in order to treat the most common type of hearing loss. While the current prototype (right) is approximately the size of a D cell battery, Draper hopes to develop an implantable version that is approximately the size of an AA battery.



even biodegradable constructs suitable for numerous ex vivo (outside the living body) and in vivo (inside the living body) applications. While these systems are still in the initial stages of development, the long-term potential of the technology promises to enable success in addressing health care challenges ranging from the systemic toxicity of drugs to organ shortages. Ex vivo systems for organ assist applications are emerging for the liver, kidney and lung, and the precision and scalability of BioMEMS fabrication techniques promise game-changing improvements in device performance and patient outcomes.

The greatest benefit from BioMEMS technologies will likely be realised through the application of implantable devices and systems. Micro scale implantable devices offer advantages including extreme levels of achievable miniaturisation; integration of multiple functions such as delivery, sensing and closed loop control; and the ability of precision micro scale and nano scale features to reproduce the

cellular micro environment to sustain long-term functionality of engineered tissues.

Treating diseases often requires repeated administration of drugs over long periods of time, ranging from months to years — and in some cases, a patient's lifetime — with precise control over dosage in order to maintain safety and efficacy. Further, delivery is often especially challenging due to difficulties in reaching the target tissue or organ. These barriers have spurred development of fully implantable, self-controlled drug delivery systems to treat diseases such as diabetes and cancer, as well as conditions like neurological disorders and vision and hearing loss. Ideally, fully implantable systems would operate in a closed-loop fashion, using data from an internal sensor to identify changing conditions and then calibrate dosage accordingly.

Although engineered-tissue constructs for replacement of organ function remain the ultimate target for tissue engineering and regenerative medicine, numerous BioMEMS-based organ-assist devices are

being pursued as interim solutions. The principal advantage of these systems — as is the case for in vitro models for discovery as well as for organ replacement — is the ability to replicate the micro environment of tissues and organs.

Improved renal, hepatic, and pulmonary-assist devices are being developed in the laboratory, principally enabled by micro fluidics and BioMEMS fabrication techniques that can be scaled up to provide the capacity needed for human therapy. While the benefits from the early generations of these technologies may be seen as they replace existing devices in intensive care units and in clinics, ultimately BioMEMS-based approaches will lead to home care and wearable systems that improve outcomes and greatly enhance the quality of life for patients.

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MEMS Technology in Real Life: A Critical Part of the Total Artificial Heart

MEMS sensors have a long history of playing a significant role in medical devices that contribute to improving the quality of life for a variety of conditions. Their accuracy, sensitivity and small size have contributed to increased portability and efficient operation of a range of medical devices.

MEMS pressure sensors have been used in blood pressure monitors for over 15 years. MEMS pressure and/or flow sensors are also used in CPAP (Continuous Positive Airway Pressure) devices to treat obstructive sleep apnea, improving the quality of sleep for millions of people worldwide. The size reduction of oxygen concentrators that has occurred over the past few years has given people with chronic obstructive pulmonary disease (COPD) much greater freedom to participate in more physical activities, which improves their overall health. It also helps them to maintain active lifestyles as well as the ability to travel. And now, an exciting new device, which utilises a MEMS mass flow sensor, is entering the medical field.

A Total Artificial Heart for Recovery and Bridge to Transplant

Heart failure patients were once hospitalised while awaiting a heart transplant. Now, however, a new medical device is allowing them to live at home while awaiting their new heart. The SynCardia temporary Total Artificial Heart is a bridge-to-transplant total heart replacement for patients who have end-stage heart failure of both ventricles (biventricular

failure). The Total Artificial Heart provides immediate, safe blood flow of up to 9.5 liters per minute (LPM) through both ventricles. The design of the Total Artificial Heart enables the patient's body to automatically adjust blood flow according to his or her activity level, providing more blood flow during exercise than at rest. With this improvement in circulation, the health of the patient's other vital organs often significantly improves, resulting in an overall stronger body and a better transplant candidate.

Both the right and left heart ventricles and the four native heart valves are removed. Then the device is implanted and connected to a driver unit outside the body which powers the Total Artificial Heart and contains all of the pumps, motors and associated electronics. There are no electronics in the Total Artificial Heart that is implanted into the patient's body.

SynCardia's Total Artificial Heart technology, originally used as a permanent replacement heart, was approved by the FDA in 2004 and received European and Canadian approvals in 2005 as a bridge-to-transplant for patients dying from end-stage heart failure of both ventricles. During the pivotal clinical study, the SynCardia Total Artificial



Figure: Small enough to be carried in a backpack, SynCardia's 13.5 lb Freedom driver compared to its 418-lb Big Blue predecessor.

Heart produced the highest bridge-to-transplant rate of any approved heart device: 79%. Over 900 implants of the Total account for more than 210 patient years on the Total Artificial Heart.

Miniaturisation for Patient Freedom

The Total Artificial Heart began sustaining patients in the hospital with its 418 lb Big Blue driver in the early 1980s. The Companion, a newer and smaller hospital driver, received the European CE Mark in 2009. This driver is small enough to be pulled by European Total patients on a caddy. The Companion Driver incorporates two 50 LPM MEMS flow sensors from Omron which are well suited for the application because of their high-accuracy, sensitivity and output stability. Omron provided customisation of these models to meet the faster response time required for the application.

Further miniaturisation of

the design continued, resulting in the new 13.5 lb Freedom portable driver. This driver is CE approved in Europe and is currently in an FDA-approved Investigational Device Exemption (IDE) clinical study in the US. Through the IDE clinical study, stable Total Artificial Heart patients who meet study criteria may have the option to be discharged from the hospital with the Freedom portable driver, to wait for their matching donor heart at home and in their communities.

The Freedom driver was designed to provide patients with more 'freedom' in their daily lives, both inside the hospital and at home. In addition to improving patient comfort, Freedom helps to keep healthcare costs down. When stable patients recover in the comfort of their homes, rather than in the hospital, it virtually eliminates in-hospital costs for this portion of patient care and hospital beds are freed up to care for other seriously ill patients.

Omron Keeps It Small and High-Performance

The Freedom driver uses the very compact 3 LPM flow sensor from Omron. This fast-response sensor (under 5 msec) does not require any modifications, allowing the company to use a standard off-the-shelf product. Its ultra-compact 36.6 (L) x 8 (W) x 16.8 (H) mm size, and 5.27 gram weight contributed greatly to making the Freedom driver small and light enough to be carried by the patient in a backpack.

www.syncardia.com

Dr. Randy Goodall, CEO of NanoMedical Systems; and Michael Lee, Director of Marketing, Life Science, SVTC

Quality of Life from MEMS

The semiconductor industry has been driven to constantly challenge the boundaries of material and manufacturing capabilities to meet market demand and continue to obey Moore's Law. Ever finer geometries and scales of device production are targeted to build memories with larger capacities and faster processors with higher levels of integration, all while decreasing cost per bit/transistor. Semiconductor processing equipment and material innovations are now being applied to situations that are not in the realm of memories and processors but rather in markets such as energy, life science research and drug delivery, to name a few. This innovative application of semiconductor technology has been described best as 'More than Moore,' and it will have as dramatic an impact on quality of life as Moore's Law has had on productivity.

Quality of life is defined by many factors but none so intimate and immediate as our health. It is inevitable that defects, disease, damage and decline of our biological systems will occur. Modern medicine has developed an arsenal of increasingly sophisticated drugs and biological molecules to treat these. However, the chemo-psychological balance of our systems can be significantly disrupted by the treatments themselves. Challenges of conventional drug delivery include: lowered efficacy and side-effects from the ups and downs of pills and injections; non-personalised dosing, duration and behaviour; poor compliance with treatments that are lifestyle-invasive and produce physical or emotional discomfort; and higher healthcare costs to society.

Personalised Molecular Drug-delivery Systems

The NanoMedical Systems (NMS) Personalized Molecular Drug-delivery System (PMDS), Figure 1, is a family of small implantable drug-delivery devices that slowly release a therapeutic agent from a reservoir over a period of weeks to months. A nanochannel delivery system (nDS) embodied on a silicon chip regulates the flow of therapeutic molecules out of the device. The PMDS is a new alternative to current treatments that require frequent and routine injections, clinical visits or other compliance-lowering complications. The

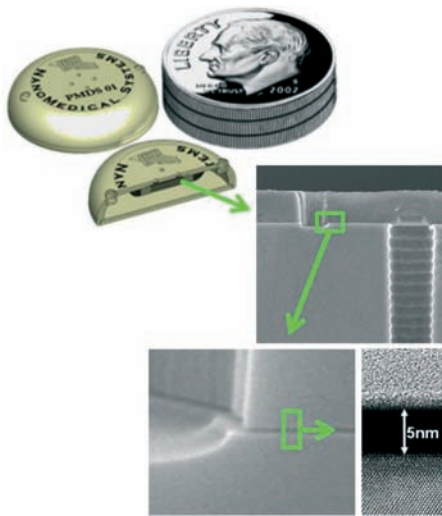


Figure 1: Example of the NanoMedical Systems PMDS device. Once implanted just under the skin, this small capsule releases a drug for many months. As seen in the cross-section, the nano channel chip, fabricated at SVTC, regulates the out-flow of the drug molecules. Electron-microscope images show details of one of more than a half-million 5 nm channels on the chip. In the lower right, an image of a nano channel magnified 2 billion times shows the atomic structure of silicon on the bottom and the amorphous ceramic layer above. Only with advanced MEMS and nano fabrication can this technology be made available in a size so small that it does not interfere with a patient's lifestyle.

first-generation PMDS, now in product feasibility assessment, is intended to increase efficacy and safety while reducing side effects. It supports a wide range of potential therapeutic agents with minimal formulation requirements. The ultimate PMDS embodiment represents a new pharmaceutical paradigm: a smart, communicating, actively controlled in-body system that functions like an artificial gland.

At the core of the nDS technology is the nano channel. In the NanoMedical Systems device, the nano channels are fabricated at densities of $\sim 100,000/\text{mm}^2$. While the nanochannels are a few microns wide and long (the 'big' dimensions), they are literally fabricated in the range of 2—50 nanometers in height — precision-sized according to the drug molecule or nano particle of interest. University research has demonstrated that nano channels offer a constrained release to drug molecules in high concentration when the nano channel dimension is near the size

of the particular molecule, providing constant delivery over a long period. Because the NMS nano fluidic chip is built on silicon with advanced deposition and etching technologies, integration of micro-scale wiring is straightforward. This enables modulation of the kinetics of molecules moving in the device. These capabilities of the NMS device are enabled by the advanced semiconductor capabilities at SVTC.

The MEMS Connection

Historically, MEMS arose on old equipment sets. At SVTC, however, the most leading-edge semiconductor equipment, processes and materials are used to create revolutionary devices like the implantable nDS nanofluidics chip. SVTC's IP encompasses deep ultraviolet (DUV) lithography and chemical-mechanical polishing (CMP) as well as a wide array of ceramics available via atomic layer and thin film deposition. The ceramics are essential to protecting other conventional MEMS/NEMS structural materials that body chemistry would otherwise dissolve — making them particularly important for in-body systems. It also includes on-conventional CMOS materials as diverse as III-V compounds, carbon nanotubes, and molecular vapour deposition of organic compounds for biocompatible surfaces support a variety of application requirements.

SVTC has successfully collaborated with customers in deploying 'More than Moore' technologies in the semiconductor, life science, aerospace and defense, renewable energy, consumer and communications markets.

Quality of life improvements should be available to everyone. In order to realise this vision in healthcare, we must seek to evolve low-cost, sophisticated treatment systems out of today's simple therapeutic concepts. As it did in the electronics industry, advanced semiconductor processing will lead the way, converging with nano technology and biotechnology to create new paradigms of treatment that we can only imagine today. NanoMedical Systems and SVTC are working together to make this convergence a meaningful and commercial reality.