Plug and Play Microsystems (MEMS) Technology into an Engineering and Technology Program

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Abstract

Advanced engineering and technology programs are under constant pressure to continually evolve and engage students. The MEMS (microsystems) industry continues to grow at a rapid rate, 10-15% CAGR, fueling a demand for additional technicians and engineers. Developing new curricula to support these new technologies is time-consuming and costly for engineering education departments. The Southwest Center from Microsystems Education (SCME), a National Science Foundation-funded Advanced Technological Education Center, (DUE #1205138) provides support, training, mentoring, and materials targeting undergraduate tech programs, two-year, four-year, and secondary STEM programs.

This paper gives readers an overview of the SCME's wide range of modular educational resources that may be adapted, modified, and inserted into existing programs or used to create new courses and program offerings. The SCME has more than 40 learning modules, multi-day cleanroom workshops at several sites, online streaming animations, lectures, archived webinars, and a dozen hands-on classroom kits available, enabling evolving technical and STEM programs to maintain relevancy and upgrade students skills. These materials include topics ranging from cleanroom protocol and safety, MEMS history and applications, BioMEMS, and microsystems fabrication. This paper provides an overview of SCME educational materials, hands-on kits, and Web resources. The SCME encourages collaboration and can support professional development.

What Are MEMS?

Microelectromechanical systems (MEMS) are small systems consisting of devices fabricated at the micron scale. MEMS typically fall into two categories: sensors or actuators. Actuators include devices such as inkjet print heads, digital mirror micro displays, and microfluidic pumps. MEMS sensors measure inertia, pressure, chemical, and magnetic parameters, for example.

Inertial sensors are used in automotive crash bag deployment, safety and navigation systems, as well as heart pace-makers and smart phones. They keep track of motion when global positioning system (GPS) signals fail (navigating in buildings or within cities with high-rise buildings). These also provide data used to adjust the heart rate in a pacemaker and inputs for gaming applications.

Micro mirror-based display systems are dominated by the Texas Instruments digital mirror device, part of the DLP system. These chips consist of 1M to 8M individually controlled tilt mirrors, each measuring between 14 to 20 microns square. These systems are found in mobile phone projection systems and full cinema digital display technologies covering a wide range of display resolutions.

The most prevalent micro-fluidic device is the inkjet print head. These MEMS systems consist of micro fluidic pumps, channels, and nozzles that deliver micro-droplets at high rates over large areas to produce photographic quality images on paper. Inkjet print heads were the number one MEMS devices in the early 2000s and still make up a large portion of the MEMS market. HP is currently ranked #4 top MEMS manufacturer, with over $600M revenue in 2012.

Pressures sensors were arguably the first high volume MEMS device. Kulite, one of the leaders in micro pressure sensor technology, was founded in 1959 by Dr. Anthony Kulite and was the first commercially available source of silicon strain gauges [1]. Today, this $2B market segment provides micro-pressure sensors found in aviation, automotive, consumer, and medical applications.

Bio-medical microsystems, or BioMEMS, are one of the fastest growing segments in the MEMS industry. These include a variety of therapeutic applications from artificial retinas, cochlear implants, neural implants, glucose sensing, insulin dispensing, and pacemakers to diagnostic lab-on-a-chip applications including DNA microarray, and point-of-care systems.

An increasing number of MEMS devices includes the micro-cantilever component. Cantilevers are part of inertial systems, chemical sensor arrays, memory arrays, atomic force microscopes, and radio frequency (RF) switches.

There are hundreds of MEMS products and applications that can be utilized to engage the undergraduate engineering or technician student. The SCME has put together a series of learning modules, hands-on kits, videos, and animations to support STEM education utilizing MEMS as the delivery vehicle.

How Are MEMS Made?

MEMS differ from computer chips as they not only move electrons but also small mechanical components. MEMS sensors need to connect with the environment requiring fluidic, gas, light input/output channels as well as electrical connections. MEMS fabrication includes the typical complementary metal oxide semiconductor (CMOS) materials and processes found in the computer chip industry but also other processes such as LIGA, micro-plastic injection molding, electroplating, electrostatic discharge deposition, laser ablation, and micromachining.

The SCME has included materials that describe three of the most utilized MEMS process categories: surface micromachining, bulk micromachining, and LIGA.

Surface micromachining is one of the most utilized technologies for producing inertial sensors, mirror devices and the like. This process is very close to that used in CMOS semiconductor fabrication and is based on building the MEMS devices on a crystalline silicon substrate. The devices are made by depositing alternating patterned layers of structural and sacrificial layers. The sacrificial layers are removed at the end of the process to release the moving parts. In semiconductors, the dielectric layers between the conductive layers are not removed.

Bulk micromachining is used to remove relatively large amounts of starting material, for example, when making pressure sensors, there is a need to create a reference chamber by removing crystalline silicon through anisotropic wet etching. It is also used to create free-standing cantilever arrays or RF micro-switches. Channels for microfluidic applications and through chip vias (holes) are also made with bulk micromachining methods.

LIGA was first developed in Germany to produce high-aspect ratio micro parts. LIGA stands for lithographie, galvanoformung, abformung and came to commercialization in the 1990s. The process consists of exposing a relatively thick material, such as PMMA, with highly collimated x-ray source (synchrotron radiation), subsequently developing out the unexposed areas, resulting in a high-aspect ratio mold. This mold is then filled with metal through an electroplating process. The metal form is removed from the mold and can be used a stamp or as the actual part. Micro, high-aspect ratio stamps are used to repeatedly make micro-fluidic channels in plastic, for example.

Why MEMS? Industry Growth and Need

MEMS and microsystems continue to grow at double digit compounded annual growth rates (CAGR) as predicted by Yole Développement Group, the leading microsystems market research company. MEMS chips are found in biotechnology, transportation, homeland security, and consumer product applications. Common examples include crash bag sensor systems, inkjet print heads, DLP televisions and projection systems, and microphones and motion sensors found in smart phones, remote controls, biometrics, and game controllers.

The most ubiquitous of our modern gadgets is the smart phone, the most advanced having over 15 MEMS devices including, but not limited to, accelerometers, gyroscope, electronic compass, pressure sensor, BAW filter, BAW duplexers, RF switches, TCXO oscillators, micro mirror display projection, CMOS image sensor, auto focus actuator, front and rear cameras, ALS, proximity sensors, and micro-displays with touch interaction. MEMS cell phone unit shipments comprised 45% of the total market in 2010 and are expected to grow to 50% of by 2015; conversely, automotive market share has dropped from 75% of the MEMS devices shipped in 2005 down to 30% in 2010 and expected to be only 20% of the market in 2015 [2]. The overall MEMS market continues to grow even in the current economic downturn as the younger generation considers smart phones a necessity, not a luxury; being socially connected is more important than owning a car or a home [2]. This also supports the concept of integrating engaging microsystems educational materials to enhance STEM core classes at the high school level.

In addition to enamoring students with the small devices within the smart phone, BioMetrics is another engaging topic for students. It is predicted that in the near future, wireless MEMS-based devices “in your home will keep tabs on your medical status every day, as you go about your daily routine” [4]. Biometric sensors and ambient monitoring will become commonplace and could save up to $6.4B annually for the estimated 1.27 million US patients at risk of heart failure through reduced hospital admissions:

> . . . we are at an inflection point now, where wireless connectivity, personal cellular devices, pervasive sensing technologies, social networks, and data analytics are mature enough to make wireless medicine a reality. And there is a will as never before to find a way to reduce crippling health care costs. Already, new devices allow diseases like diabetes and chronic heart failure to be closely monitored outside the doctor's office; tools for tracking chronic kidney disease and a variety of lung disorders are sure to follow. Eventually, most health care will occur not during occasional visits to doctors' offices, clinics, or hospitals but continuously, during ordinary activities in people's home . . . [5].

In 2011, the overall MEMS device market reached $10B, followed by a 10% growth in 2012 to over $11B, and is expected to continue this 10% growth rate in 2013 [6]. The 2012 MEMS growth is contrasted by the 2% contraction of the semiconductor industry in 2012. Inertial sensors overtook display and inkjet print technologies, while individual MEMS microphone companies saw 20-90% growth rate supplying the smart phone industry. Inertial sensors have moved from the classic 3-axis stand-alone units to 6-axis integrated systems, and 9-axis accelerometer systems are on the horizon for widespread integration. The overall accelerator chip size has dropped from 3.5x5mm to 1.6x1.6mm, between 2009 and 2014. Even though the price per accelerometer has dropped below $1 in 2013, the overall accelerometer market share is $3.5B out of the $11B total 2012 market [7].

Not only are MEMS found in consumer products but also in biomedical applications. These systems use a variety of micro- and nano-scale manufacturing processes and materials outside of those found in the semiconductor industry. The BioMEMS market continues its rapid growth resulting in the microfluidic sector growing from $1.5B in 2010 to a project $4.5B by 2015 [6].

The total MEMS device market for 2011 was projected at $10B and is expected to grow to $19.5B by 2016, at an average of 14% CAGR [8] . Most recent projections indicate a 12-13% CAGR for the overall MEMS market with an expected $22.5B, 23 billion part market by 2018 [6].

As these sources show, the MEMS manufacturing industry is growing at a rapid pace which should translate into a higher demand for tech-educated graduates. The SCME is focused on technician education and tasked itself to survey the industry and determine the overall demand for technicians. The survey was completed in 2012. Over 60 small, medium, and large-scale enterprises contributed to the survey covering a range of industries including MEMS, semiconductor and capital equipment/support companies. The results of this survey indicated that all sectors planned to increase hiring into new positions from 10% to 100%.

The larger, established semiconductor fabrication facilities planned to hire 10%, evenly split between new positions and replacement, while small, MEMS startups typically planned to double their tech staff in two years with mostly new positions [12]. This supports the evolution of technical and STEM programs to include MEMS elements.

The SCME has an industry advisory board made up of small, medium, and large-scale enterprises spanning the semiconductor and microsystems industry. Meetings are held one to twice a year, and industry input is sought as, well as review of educational materials.

MEMS in STEM—SCME's Approach

The Southwest Center for Microsystems Education (SCME) strives to increase the educational capacity to produce technologists skilled in assisting microsystem research, design, and commercialization activities.

The SCME regional center responds to the need in the rapidly emerging microsystems industry for the adaptation, development, and dissemination of educational materials and professional development for educators. To support these activities, the SCME embraces a continuous improvement methodology adjusting to the needs and requests of its stakeholders: students, educators and industry. The key is to be constantly evolving.

The SCME has developed a series of educational resources to support the technician capacity building for the microsystems industry. The skills and knowledge required by technicians have been identified by a series of industry meetings, surveys and experience of the PI gained while in the semiconductor industry.

It was decided early on to leverage the fabrication process of a simple micro-pressure sensor as a guide to constructing a series of educational modules. The essential question "What does a technician need to know to fabricate and understand the workings of a micro-pressure sensor?" was used as a guide. This process resulted in a series of topics:

Cleanroom Fabrication Process
- Photolithography
- Dry and wet etch
- Thin film deposition & oxidation
- Materials

Electronics
- Wheatstone Bridge
- Transducer principals

Safety
- Hazardous materials
- Chemical lab safety
- Material safety data sheet

- Interpreting labels
- Personal protective equipment
- MTTC safety course
-

As these core components were written, and courses developed, it was found that other modules needed to be developed to answer the following questions:

- *What are MEMS and where are they used?*
    - Application overview
    - BioMEMS overview

- *How do they work?*
    - Micro-cantilever
    - Micro-pumps

- *What is the history of microsystems?*

SCME realized early on that BioMEMS was a large, rapidly growing segment of the MEMS industry. Leveraging the Bio-LINK ATE National center, SCME collaborated with several bio-tech subject matter experts to create a series of BioMEMS related topics covering a suite of BioMEMS topics:

- Overview
- Applications
- DNA overview and microarrays
- Bio-molecular applications
- Clinical laboratory techniques
- Diagnostics and therapeutics
- Environmental and bioterrorism
- Regulations

In addition to the above series of topical learning modules, SCME has created supplemental materials including collaboration on two films by Ruth Carranza and Silicon Run [13]:

- "MEMS: Making Micro Machines"
- "Nanotechnology: The World beyond Micro"

SCME has created supporting educational modules that include background information and activities to augment the videos and also the script.

Additional supplemental materials include videos and animations available on the SCME website [14] and the Microsystems Education YouTube Channel [15].

In response to educator requests, SCME has created a series of hands-on kits the enable teachers to bring microsystems topics to the classroom. These activities are part of the learning modules.

SCME Educational Materials Resources

NSF funding has fostered the creation and foundational development of the SCME as a fully-functioning Advanced Technology Education regional center of excellence with regional and national impacts, providing a sound basis for continued expansion of its local, regional, and national outreach and dissemination efforts. SCME has established competencies in the development and adaptation of modular, readily updated, and easily disseminated educational materials for the microsystems field. These materials are organized into units referred to as SCOs (shareable content objects). The development process is loosely related to the shareable content object reference model (SCORM), first conceived by the Department of Defense in 1999, as part of the Advanced Distributed Learning Initiative [16, [17]. It should be noted that the SCME modules are not fully "SCORM-compliant" but were developed to be used as stand-alone learning modules.

Each "plug and play" learning module consists of several SCO's: 1) PKs, primary knowledge; 2) FAs, assessments; and 3) ACs, activities, which include homework and lab units as well as the hands-on kit activities. There are also learning maps to assist the educator in developing lessons plans. These are designed so that an instructor can utilize a series of modules to build an Introduction to MEMS course, for example, or utilize one module or one or more of its components to add emerging technologies content to an existing course. For example, the Wheatstone Bridge Micro-Pressures Sensor module is often integrated into electronics courses.

The educational written materials are all available on the SCME website. Educators are encouraged to peruse the site and create an account. The website provides resources both for educators and students. Every one of the over 40 educational learning modules includes both "Instructor" and "Participant" (student) guides. The instructor guides are available to registered users and include notes answers to activities, and assessments as well as PowerPoint presentation files. Registered users can also access the original Word documents so that they can modify these lessons to meet their needs and those of their students. These downloadable materials are free.

Key Resource Links

- Home page - http://scme-nm.org/
- Educational materials [18]
- YouTube microsystems education channel [19]
- Hands-on kits [20] and kit store [21]

Listing Of Hand-On Kits Available

1. Modeling a Micro-Pressure Sensor
2. Learning Microsystems Through Problem Solving
3. Liga Micromachining-Lithography & Electroplating
4. Surface Micromachining – Lift Off Process
5. Bulk Micromachining – An Etch Process
6. Micro Pressure Sensor Process
7. Science of Thin Films
8. Crystallography
9. Microcantilever Model
10. DNA Microarray Model
11. Nanotechnology: World beyond Nano
12. MEMS: Making MicroMachines

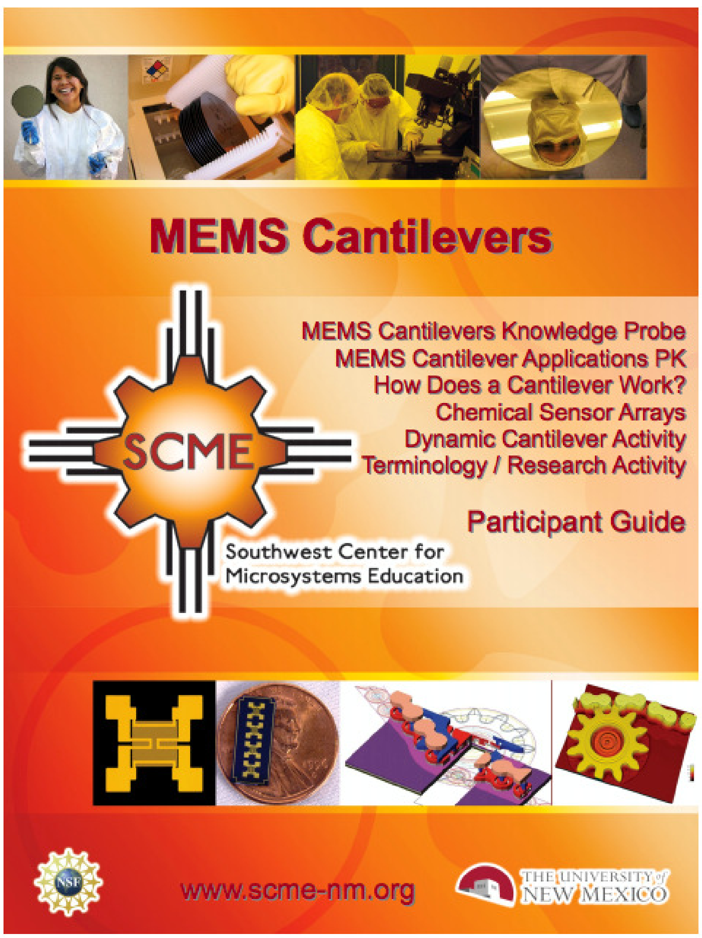

Figure 1. Example of a learning module cover with a listing of included SCO's. The Dynamic Cantilever Activity is one of the dozen kits available.

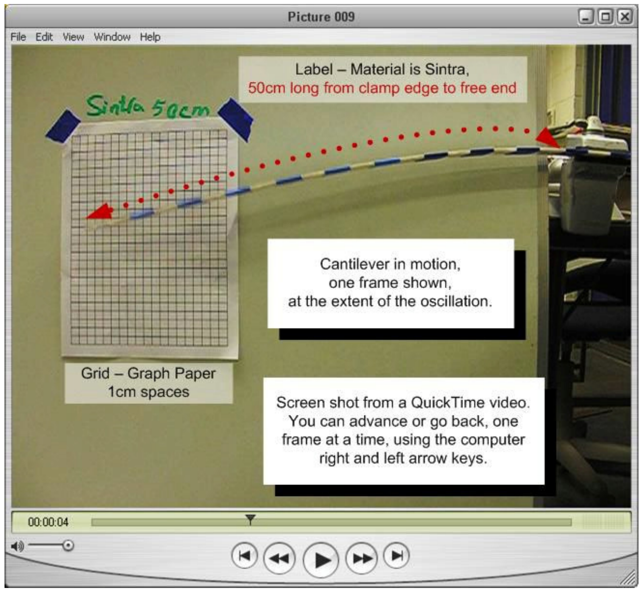

Figure 2. Image of how to acquire frequency vs. mass added,
found in the Microcantilever Model kit.

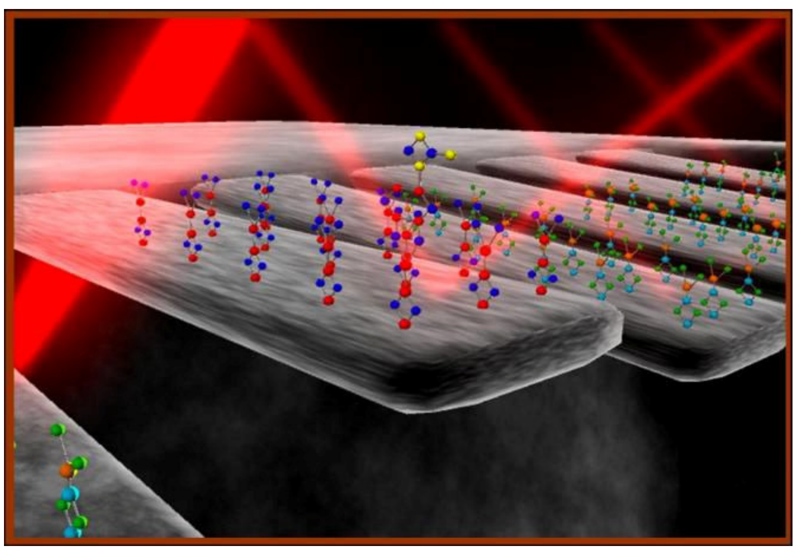

Figure 3. Screenshot from one of the supplemental microcantilever videos
used to describe the operation of a chemical sensor array.

Professional Development Resources

The center also provides professional development resources and opportunities to educators. These include half- to full-day workshops at our site and partner sites, conferences, and webinars. We also provide a 3-5 day pressure sensor workshop whereby participants go through an intensive training regimen that includes cleanroom experiences in safety, protocol, and fabrication processes. In parallel, participants participate in workshops to learn how to bring these concepts to their students in the classroom. Several of the SCME kits are utilized in these multi-day pressure sensor workshop sessions.

Figure 4. Pressure Sensor workshop at the University of New Mexico's Manufacturing Training and Technology Center. Participants display the wafers that they produced.

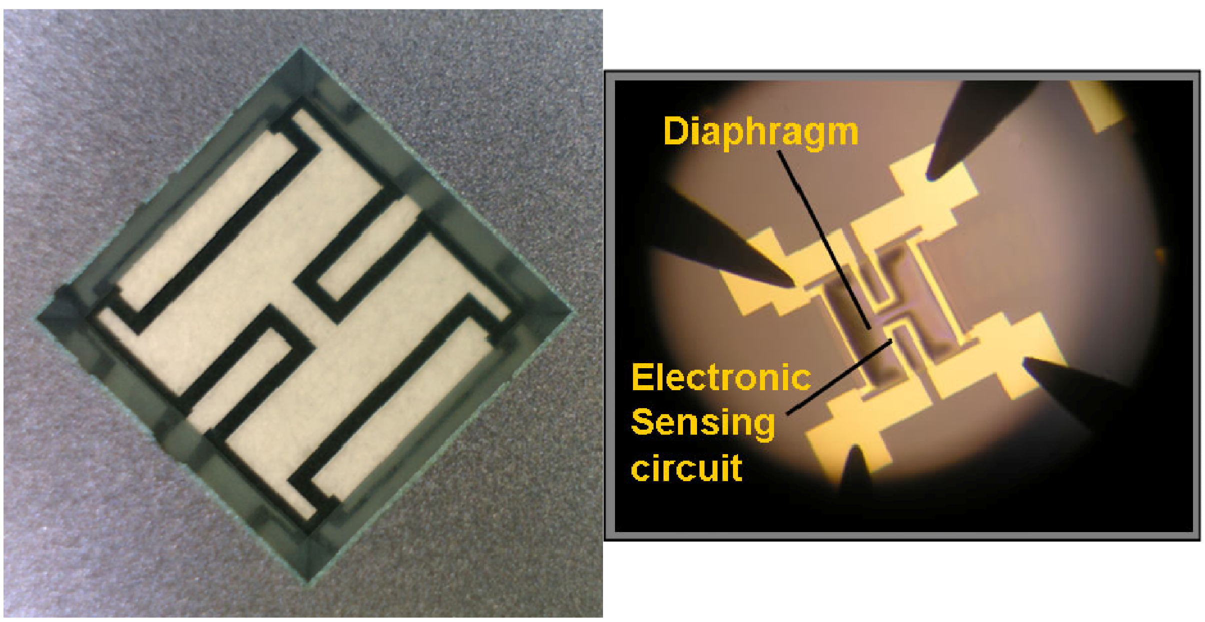

Figure 5. Close up view of the completed micro-pressure sensor: looking from the backside of the wafer through the anisotropically etched crystalline silicon (left); wafer front side and the Wheatstone bridge circuit being probed (right)

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More recently, SCME is in the process of creating a series of online short courses modeled on our learning modules and kits. The online courses can be customized for individual organizations and/or educator needs. These will provide additional support to increase the utilization rate of SCME materials. Educators will be able to "flip the classroom" by assigning units to their students and leveraging SCME created lectures, videos, animations and online resources. The short courses are also used to prepare participants for workshops. These online course resources utilize an open source platform, Moodle, plugged into the Joomla! website content management system, making it very cost effective for all stakeholders.

Summary

MEMS typically contain an integrated set of otherwise disparate technologies (e.g., mechanics, fluidics, materials, energy, photonics, biology, etc.) that span the entire spectrum of STEM components. Moreover, MEMS are one of the last bastions of hands-on learning, as colleges and universities move to replace physical labs with computer stations and simulators. The challenge is to engage and develop an agile, well-educated workforce to support this business growth and range of needed skills.

To continually evolve innovative STEM and technical programs, conventional technical high schools, colleges, and universities have the responsibility to seek out and implement innovative, emerging, and technically engaging educational materials for their students. Given today's economy, these educational organizations may not have the resources (financial as well as expertise) to teach technically advanced topics. Over the last 20 years, the National Science Foundation, through its Advanced Technological Education program, has funded many ATE centers across the country to advance the technician-level workforce in the United States. One of these centers is the SCME located at the University of New Mexico.

The SCME website, http://scme-nm.org/, has all of the written materials available for free download. Teachers are encouraged to register and gain access to additional instructor materials and resources. The kit store allows educators to order kits online for reasonable costs; all proceeds are used to replenish the kit stock. Webinars are also given, and there is a series of over a dozen archived and available. Workshops are provided at the UNM site as well as the partner institutions, and these are generally free. The annual Micro-Nano Tech Conference is co-sponsored and hosted by SCME and the nano ATE Centers (NACK, Nano-Link, SHINE, NEATEC) as well as MATEC. All of these centers also have a vast set of educational materials available to the innovated educator [22, 23].

References

[1] Kulite. (2011). Retrieved from http://www.kulite.com/
[2] SEMICO Research Corporation. (2011, March 22). *EMS Growth: Changing Markets, Changing Applications*. Retrieved from http://www.semico.com/press/press.asp?id=277

[3] Nielson Company. (2010, December). *Mobile Youth Around the World*. Retrieved from http://www.nielsen.com/us/en/insights/reports-downloads/2010/mobile-youth-around-the-world.html
[4] Charette, B. (2011, October 5). Digital Technologies Will Soon Deliver Daily Diagnosis. *IEEE Spectrum Computerwise*. Retrieved from http://newsmanager.commpartners.com/ieeecw/issues/2011-10-05-email.html
[5] Smith, J. M. (2011, October). Wireless Health Care. *IEEE Spectrum Inside Technology*. Retrieved from http://spectrum.ieee.org/biomedical/devices/wireless-health-care
[6] Yole Development Group. (2013, July 29). Status of the MEMS Industry 2013 Report. *I-Micronews, Market and Technology Reports*. Retrieved from http://www.i-micronews.com/reports/Status-MEMS-Industry-2013/1/384/
[7] Yole Development Group. (2014, 28 March). Inertial MEMS Manufacturing Trends 2014. *I-Micronews, Market and Technology Reports*. Retrieved from http://www.i-micronews.com/reports/Inertial-MEMS-Manufacturing-Trends-2014-Volumes-1-2/1/423/
[8] Eloy, J. C. (2011). MEMS Industry Evolution: from Devices to Function. Semicon West. Retrieved from http://semiconwest.org/sites/semiconwest.org/files/JC%20Eloy.Yole_.pdf
[9] Doe, P. (2011, June 7). The Future of MEMS: Rethinking Business Strategies and Manufacturing Technology for Volume Systems Markets—ElectroIQ. *ElectroIO—Electronic Manufacturing Industry News for Semiconductors, Photovoltaics, Advanced Packaging and Nanotechnology*. Retrieved from http://www.electroiq.com/articles/stm/2011/06/the-future-of-mems.html
[10] Cao, A. (3022, January). Medical Device Makers Turn to Microsystems to Gather Information from inside the Body. *MEMS Trends*, issue 5. Retrieved from http://www.i-micronews.com
[11] Lightman, K. (2011). MEMS in Motion Sensing: What's Cooking. *Micro Manufacturing*. Retrieved from http://www.micromanu.com/img/static/MTR%20mig%20article.pdf
[12] Pleil, Matthias W. (2013). Microsystems Industry Mapping Project. *Micro Nano Technology Conference*, Minneapolis.
[13] Silicon Run. (2014).Silicon Run Productions – Semiconductor and Technology Videos. Retrieved from http://siliconrun.com/index.shtml
[14] Southwest Center for Microsystems Education. (2009). Retrieved from http://scme-nm.org/
[15] YouTube (2012, February). SW Center for Microsystems Education. Retrieved from https://www.youtube.com/results?search_query=microsystems+education
[16] Gonzales, C. (2005). Understanding SCORM—Best Practices for Implementing SCORM. MATEC Webinar.
[17] Office of the Deputy Under-Secretary of Defense, Director of Readiness and Training, Department of Defense. (2000, May 19). *Implementation Plan for Advanced Distributed Learning*. Retrieved from https://www.hsdl.org/?view&did=480013
[18] SCME Educational Materials. (2009, November).Retrieved from http://scme-nm.org/index.php?option=com_docman&view=docman&Itemid=226

[19] SW Center for Microsystems Education. (February, 2012). *YouTube*. Retrieved from https://www.youtube.com/user/SCME2012
[20] Southwest Center for Microsystems Education. (2009, February). *Hands-On Kits*. Retrieved from http://scmenm.org/index.php?option=com_content&view=category&id=212&Itemid=161
[21] Southwest Center for Microsystems Education.(October 2012). *MEMS Educational Kits*. Retrieved from https://secure.touchnet.com/C21597_ustores/web/store_main.jsp?STOREID=44&SINGLESTORE=true
[22] Pleil, M. W., & Massiha, G. H. (2014, March). Teach Microsystems on a Tight Budget. *Techdirections*, 18-22.
[23] Pleil, M. W. (2012). Secondary/Postsecondary Programs of Study for Microsystems Technicians. In Dan Hull. (Ed.). *Career Pathways for STEM Technicians*, 177-98.

Biography

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