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Perspectives

A catalyst to change everything: MEMS/NEMS – a paradigm of Taiwan's nanotechnology program

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Background

With a population of 23 million people and a total island area of 36,000 square kilometers, Taiwan has been continually raising the competitiveness of its technology industries over the last forty years. As it stands now, Taiwan today has many industries with production volume or sales revenue ranked in the top three worldwide. Out of these industries, the most notable ones are the IC foundries, liquid crystal displays (LCD), personal or notebook computers, and scanners. Considering that three fifth of Taiwan's land is mountainous area, Taiwan's economy has never been based on purely natural resources. Taiwan's highly educated, ethical, and dedicated work forces have always been prime in the world. In addition, Taiwan's higher educational institutes have risen with the county's economic development and the drive to continuously improve its international standing. Furthermore, Taiwan's Industrial Technology Research Institute (ITRI), established 25 years ago, has grown into a powerhouse with more than 6,000 researchers dedicated to rapidly converting academic research results into commercial products. The success of Taiwan's foundries has been a milestone for ITRI's achievements so far. With Confucius teachings well embedded into Taiwan's root culture, respect of knowledge and respect of scholars flourish today more than ever. Armed with such kind of cultural advantages, Taiwan's mindset has always been on 'manufacturing for the world.' This kind of paradigm has served Taiwan well for the last 50 years. However, the economic growth in Mainland China over the last 10 years has triggered a very significant global manufacturing cost drop. With China appearing as a new manufacturing powerhouse, a global low-profit era is inevitable. As Taiwan is located geographically very close to China, the impact is even more substantial. To help the local industries maintain or even improve their competitiveness and to continuously uplift the standard of living of its people, the Taiwan government is using every means to transform itself. Nanotechnology, System-on-a-Chip (SoC), and Genomedicine have been chosen as platforms to push the whole nation forward. To make sure that resources are properly allocated to the above-mentioned areas, all have been included into Taiwan's National Science and Technology (S&T) Priority Program. To be included in the Priority Program, each of the programs must be proposed through various strategy meetings, which takes months of planning and review. However, once approved, a National Program Office is set up to coordinate all related activities across different ministries. It also means that these programs will have the highest priority in competing for government research and development funds.

MEMS and the knowledge supply chain

To examine the perspective of Taiwan's nanotechnology program, the strategy, and experiences learned, current transitions of Taiwan's Micro-Electro-Mechanical-Systems (MEMS) program serve as a good vehicle to reflect some basic thoughts in Taiwan towards its pursuit of the micro or the nano world. Technology transfer based on a knowledge supply chain concept has always been an integral perspective for Taiwan's strategy in MEMS development as more than 90% of the companies in Taiwan are small and medium enterprises. One of the underlying directives for Taiwan's MEMS program has been to incubate MEMS industries. To complement technology transfers and industrial development, Taiwan's academia and R&D institutes have placed a very strong emphasis on turning out enough numbers of students or engineers with the proper backgrounds. Continuing Taiwan's long-term mindset related to 'manufacturing for the world,' Taiwan's MEMS program has adopted 'Support worldwide MEMS Fabless' as its paradigm (Figure 1). In other words, Taiwan is trying to repeat its successful experience with CMOS foundries and again trying to transform itself into a worldwide premium MEMS foundry center. At the last count, this strategy appears to be working and has begun to bear some fruit. A series of extensive investments and the founding of several companies with a prominent portion of their targeted revenue in the MEMS area is a clear sign that such a strategy is working. With a significant number of companies being set up in a very short time period (Table 1), the demand to have more qualified engineers in the MEMS area has been dramatically increasing. Also with this rapid increase in demand, human resources will also soon become a bottleneck in Taiwan's pursuit of high profile MEMS industries. This shortage is common to today's knowledge-based economy, which agrees well with the century-long Confucius teaching, 'It takes 10 years to grow a tree but it takes 100 years to make a man.'

Roots of core facility sharing and cross-discipline training

Accompanying the establishment of these MEMS companies is a fundamental emphasis shift for Taiwan's MEMS program. That is, the MEMS program in Taiwan has changed from being technology-driven to being market-pulled as expectations of domestic industries towards educational and research institutes have grown out of technology development to encompass personnel training, personnel growth, as well as the identification of other business areas. In other words, there are growing demands that require more engineers with system perspectives beyond traditional interdisciplinary engineering and science backgrounds, including backgrounds in business as well as other such intellectual aspects. This cross-disciplinary requirement has had a strong influence on the planning of Taiwan's human resources for its nanotechnology program. To accommodate the perspective and demand changes, the steps taken by Taiwan's institutes have also been modified accordingly. Furthermore, with an understanding that MEMS industries will face a vast array of demands that are different from that of traditional IC foundries and as nano-technology is now becoming an important driving technology for the advancement of MEMS, the emphasis of every party involved has been re-oriented as well. More specifically, since MEMS is considered a good vehicle towards the pursuit of a top–down approach in nanotechnology and as nanotechnology is considered to be able to help MEMS advance further both technologically and systems-wise, MEMS is moving closely and rapidly with nanotechnology. Consequently, the National Science Council (NSC) of Taiwan has renamed the MEMS Technology Advancement Team Program (TATP) established six years ago, to become the MEMS and Nano-technology

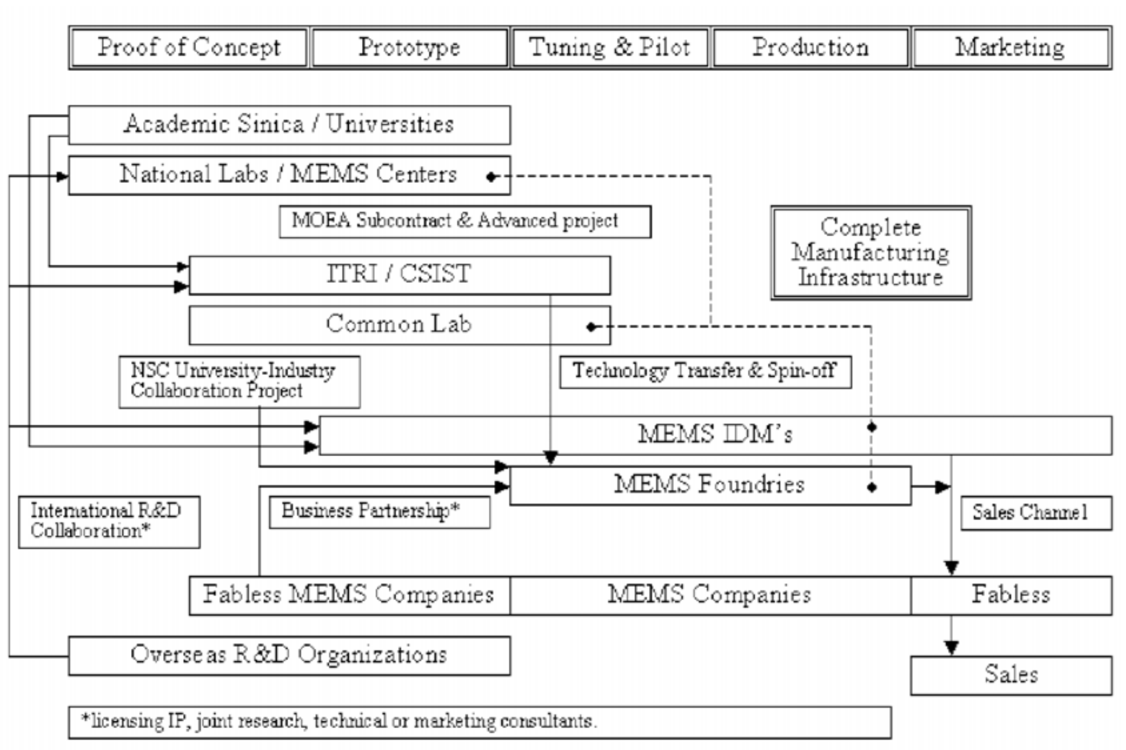

Figure 1. Operational model of Taiwan's MEMS Programs.

Table 1. MEMS investment in Taiwan

Application	Company	Investment (US $Millions)	Time	Product
Communication (optical/wireless)	8	200	1997–	Optical communication RF communication AWG Sensors/OEM/ODM Inkjet head/OEM
Bio-medical	7	55	1997–	DNA detection chip
Sensors	9	52	1997–	Pressure/CO sensor Accelerometer IR sensor
Information tech (IT)	6	80	1996–	Micro-plate DMD Micro fin Inkjet head SAW
Total	30	387	1996–	

Advancement Team Program to ensure that a nanotechnology emphasis is placed within the MEMS programs at Taiwan's academic institutes. The three NSC regional research centers, set up five years ago to capitalize on the strong attraction of MEMS to mechanical engineering faculty members and students here in Taiwan, have a total funding of over US$10 million so far. These regional centers have utilized the established MEMS equipment, clean-room facilities, and technical capabilities established in hoping to help themselves gain a competitive edge in pursuing system applications. Moving in line with a **BASIC** strategy (an acronym for **B**iology, **A**utomation, **S**emiconductor, **I**nformation Technology, and **C**ommunications) as set up in the year 2000 by TATP, the three centers placed their individual research and development emphasis on communications (Northern Regional Center), semiconductor (Central Regional Center), and bio-MEMS (Southern Regional Center), although all fields are pursued. The three centers serve as the focal points for university–industry collaboration facilitation. These experiences and the conversion processes are part of the reason that core facilities and a sharing mechanism establishment are deeply rooted in Taiwan's nanotechnology program. The operating policy for these NSC centers, which requires all users to operate the equipment themselves after passing the training and evaluation procedures implemented by each center, has proven to be invaluable to incubate the many desperately needed R&D (research and development) engineers for Taiwan's budding MEMS industries. With these NSC centers serving successfully as the vehicles for training and for R&D, the NSC is now demanding that these centers incubate collaborative group R&D projects with the hope that academic MEMS research programs can grow into the role of knowledge provider in the knowledge supply chain of industries in Taiwan. This growth path experience leaves a mark on Taiwan's nanotechnology program as well.

The CMOS advantages

It should be noted that the BASIC strategy is in line with the policy set up by Taiwan's Ministry of Economic Affairs (MOEA), which stipulates that interactions among Taiwan's different organizations must be present for an important program such as MEMS to be successful (Figure 2). This close collaboration among the different ministries demonstrates the coherent activities for Taiwan's important technology policy such as MEMS. As nanotechnology is being established as a National S&T Priority Program, which is a status that the MEMS program hoped to achieve but never realized, the close collaboration should be further strengthened. It should be noted that the year 2002 marks the sixth year since the MEMS program has been put into full execution in Taiwan. With the successful operation of the MEMS Common Lab at the ITRI Common Lab, the fundamental MEMS-related fabrication techniques have been deemed approaching maturity in Taiwan, at least in the first phase. Detailed examination of the MEMS product manufacturing indicates an intertwined relationship between MEMS and CMOS processes (Figure 3). It leads to the conclusion that further advancement of MEMS technology in Taiwan relies on the full integration of Taiwan's well-established CMOS capabilities. Utilizing CMOS capabilities to rapidly pursue a top–down approach is part of the thinking behind the planning of Taiwan's Nanotechnology S&T Priority Program as well.

The National nanotechnology program

As was mentioned above, the National Nanotechnology S&T Priority Program (NSTP[2]) Office was officially established on September 1, 2002 and the full six-year National Program with a budget of US$ 680 million (use 1 USD to 34 NTD exchange rate) will start on January 1, 2003. The overall organization planning is listed in Figure 4. It is clear from the reflection of Taiwan's MEMS program mentioned above, that this National program will again bring the Ministry of Education, MOEA, NSC Academic Sinica, and universities, hand-in-hand to layout the infrastructure for nanotechnology in order to stimulate rapid technology growth. The similarities and the differences between the Nanotechnology and the MEMS programs will be briefly reviewed herein. With a hope to move Taiwan out of the manufacturing mindset in order to react rapidly to the rise of China's manufacturing might, the planning principles of NSTP[2] are (1) achieve excellence in academic research and increase international collaborations, (2) strengthen innovative R&D personnel incubation and core facility construction/sharing to establish solid foundations, and (3) integrate excellent academic research and 'rapid commercialization capability' of research institutes to combine the unique phenomenon of 'mesoscopic world' and 'market opportunities.' In addition, the three economic goals that propel nanotechnology to

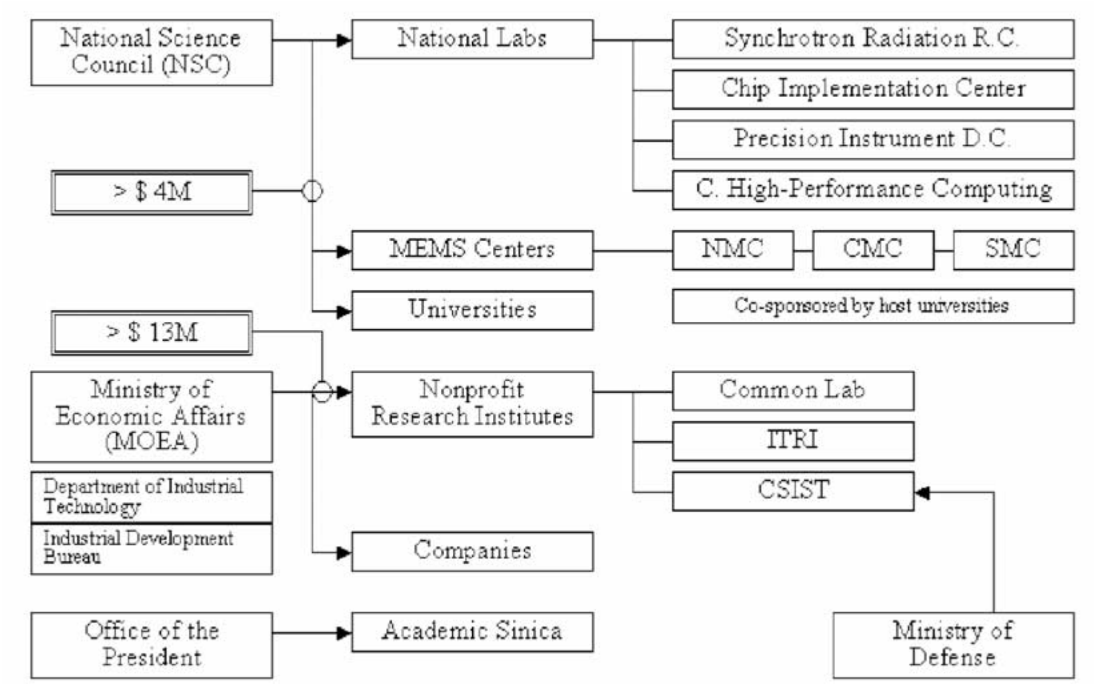

Figure 2. Infrastructure of Taiwan's MEMS Programs executed by MOEA and NSC.

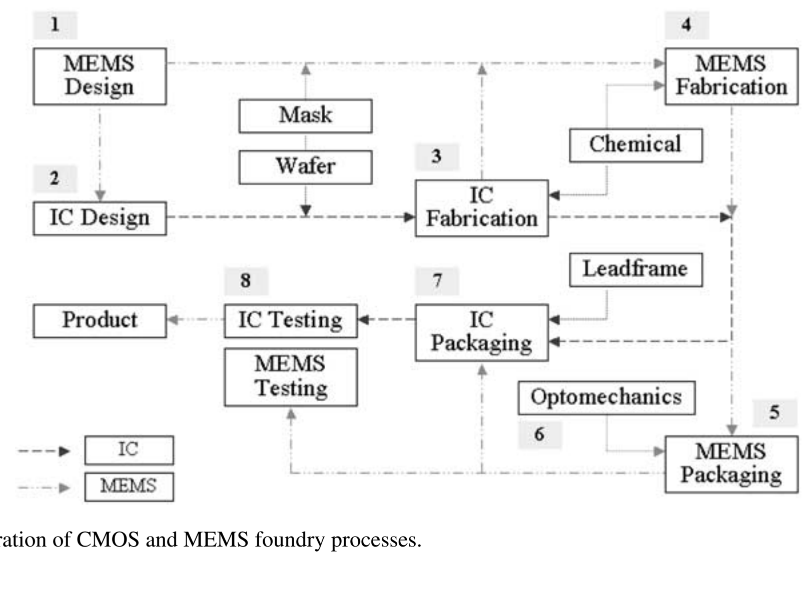

Figure 3. Close integration of CMOS and MEMS foundry processes.

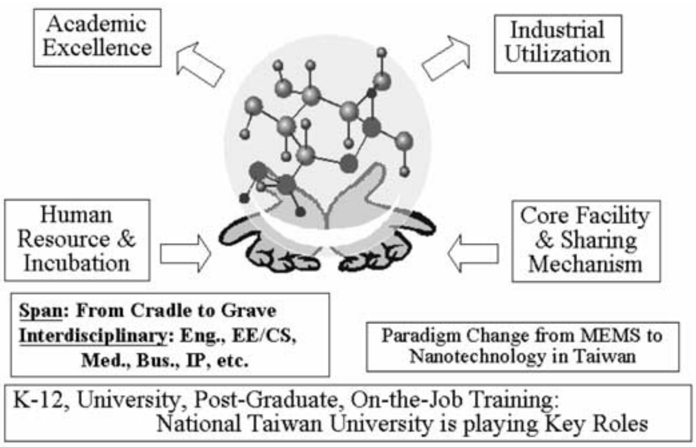

Figure 4. Organizational chart of Taiwan's Nanotechnology Program.

the National S&T Priority program in Taiwan are to (1) uplift the worldwide competitiveness of traditional industries, (2) maintain or improve the leadership position of leading industries, and (3) establish tomorrow's dream industries. Four supporting means were implemented within NSTP^2 to ensure the pursuit of the goals will be on track. That is, the NSTP^2 will use core facilities and the establishment of sharing mechanisms as well as human resources incubation as the foundation so as to seek swift industrial technology utilization/commercialization and academic excellence in nanotechnology research. It was defined early and has been repeatedly pointed out at various planning meetings that human resource incubation is the single most important factor that determines the success of Taiwan's nanotechnology program.

Since nanotechnology has been perceived as a technology and a platform that has the potential to move Taiwan away from the deeply rooted manufacturing mindset towards a more balanced perspective that encompasses R&D, manufacturing, and marketing, various new programs and measures are being put in place to drive nanotechnology personnel training. Consider the example where overall scientific knowledge of society is a pyramid, the leading researchers are the tip of the pyramid and the general public is the base that supports the pyramid. With this strong feeling, Taiwan's human resources incubation program in NSTP^2 has taken on the initiative to tackle a K-12 (kindergarten to 12th grade) program with an intention to bring nanotechnology understanding to the general public. The underlying thought is that many of the nanotechnology applications are for the long-term and that a 5th grader today may become a researcher at the post-graduate level within a 10-year time period. It is important to make sure that the fundamental understanding on nanotechnology is planted well from the start. In fact, media reporters are also targeted by this program, which plans to bring nanotechnology to the general public by using their widely available channels. In addition, to supporting the goals of NSTP^2, the human resources incubation sub-program identifies two specialties as primary goals. One specialty is the kind that can pursue or lead world-class nanotechnology R&D projects and the other is the kind that can recognize the potential commercial benefits and bring or promote the specific piece of nanotechnology to commercialization. With these two goals firmly in place, the cross-disciplinary discussions within the academic circles can then jump from the traditional integration of the science and technology arena to the one that includes intellectual properties, marketing, etc. as well. This fundamental perspective change certainly has a very strong impact on the curriculum being established across all educational levels in Taiwan. The impact of this kind program in a leading university will be further detailed later to illustrate that the 'A catalyst to change everything' paradigm used in Taiwan's NSTP^2 is indeed what its name indicates.

The academic excellence program is clearly depicted in Figure 5, which indicates that nano-materials, nano-detection & manipulation, functional devices, MEMS/NEMS (Nano-Electro-Mechanical-Systems), and Nano-bio are the fields to be used for cross-disciplinary integration. The strong emphasis on

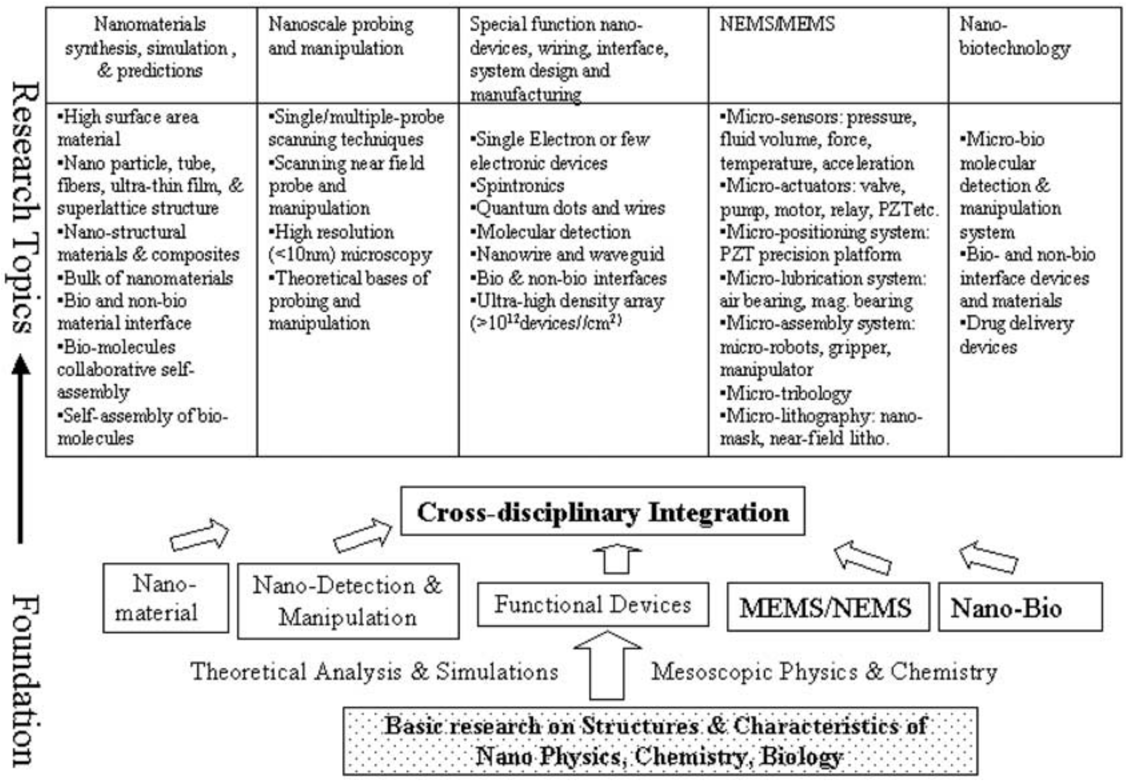

Figure 5. Scope of academic excellence sub-program.

removing the disciplinary boundaries are highlighted by the five R&D requirements associated with (1) synthesis, simulation, and prediction of nano-materials, (2) nano-scale probing and manipulation, (3) special function nano-devices, wiring, interface, system design and manufacturing, (4) NEMS/MEMS, and (5) nano-biology. These field requirements certainly provide a very good platform to foster the integration of research teams within Taiwan's universities, research institutes, and industries. The goal of this sub-program is to try to bring Taiwan's researchers to the forefront of global nanotechnology research. As was mentioned above there are three economic goals associated with Taiwan's nanotechnology program. The industrial utilization sub-program (Figure 6) within the nanotechnology program is designed to integrate the leading industries and related academic research so as to pursue the goal of making Taiwan one of the leaders in industrial applications of nanotechnology globally. To pursue this goal, the funding related to the industrial utilization sub-program is distributed according to a 20+/60/20− rule, which essentially states that (1) 20 + % of the funding will be targeted towards nanotechnology with short-term commercial application potentials and the traditional industries will be the main focus of this part of the funding, (2) 60% of the R&D resources is to be invested in the technological fields that will impact future competitiveness of Taiwan industries strategically and where a roadmap to achieve an 'order of magnitude in cost-performance ratio' has been drawn up within a five-year timeframe, and (3) less than 20% of the project will concentrate on the exploratory studies for potential applications that are 10 years away in order to foster collaboration among industrial and academic research institutes as well as leading international teams so as to deepen the R&D foundation in Taiwan.

Changes effected by National nanotechnology program

Taking core facilities and sharing mechanism establishment as an example, the successful lessons of founding

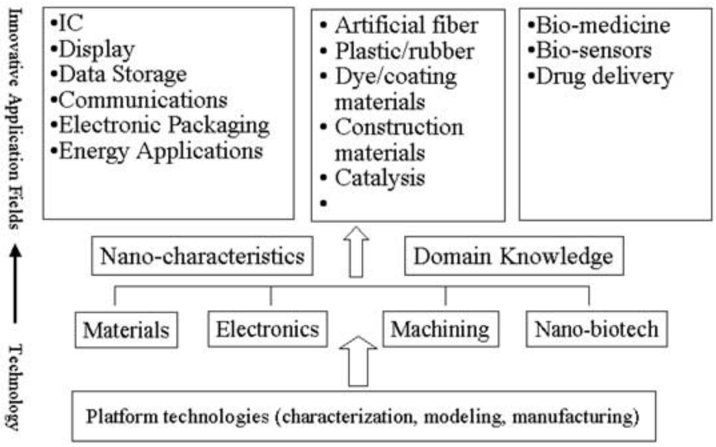

Figure 6. Scope of industrial utilization sub-program.

the three MEMS center, the ITRI Common Lab, and then the MEMS companies certainly have a very strong influence towards planning Taiwan's pursuit of nanotechnology. On the other hand, the fact that nanotechnology has achieved a National S&T Priority Program Status in Taiwan certainly means that nanotechnology will have a fundamental impact on every aspect of R&D in Taiwan. Some of these interactions will be examined herein. ITRI, known worldwide for successful incubation of Taiwanese semi-conductor industries, has formed a Nanotechnology Research Center (NTRC) as of January 2002 in response to nanotechnology becoming a National Program here in Taiwan. Its strategy focuses on seeking and turning micro-world's phenomena into market opportunities, transforming domestic leading industries rapidly into nanotechnology related industries, and combining universities research excellence to retain leading competency. Nano-materials and nano-electronics are now taken as the major core projects, a result of which has been to build an open laboratory with more than 50% of the laboratory space to be dedicated for public use. Existing ITRI capabilities in nanotechnology include nano-particles, carbon nano-tubes, carbon nano-capsules, quantum dot lasing, and nano-woven structure separators for energy storage devices that have been transferred for commercial Ni–H battery. The facilities at NTRC are being built in a full-blown manner at this moment. With this facility scheduled to open by the end of year 2002, it is expected that this center will become a catalyst to facilitate close integration between ITRI and the academic circles both domestically and internationally. In fact, ITRI is using nanotechnology as a focal point to establish joint research centers with various leading universities in Taiwan, which clearly demonstrates that nanotechnology is changing the research landscape on this island. To strengthen the foundations of a top–down approach for nanotechnology, CMOS and MEMS integration continues to play a key role in Taiwan's nanotechnology program. With MEMS being a good candidate for a top–down approach, the three NSC centers and the ITRI Common Lab are extending their capabilities to the nanotechnology arena. A few centers with their emphasis on a bottom–up approach are also being planned to bring more a nanotechnology flavor to these centers. Integrating the old and the new centers to form an effective collaboration network is deemed a must when reviewing proposals to establish nanotechnology centers. Taking the Northern-Region MEMS Center (NR-MEMSC) located within National Taiwan University (NTU) as an example, NR-MEMSC has established all MEMS facilities including MEMS CAD capabilities over the last five years. Up to now, it has built a reputation of mutual trust with more than 650 users that come from 35 institutions, and 10 industries. In 2001, the training program provided a total of 207 courses and 1652 trainee-times. The use of equipment reaches a daily average of 5.4 h and 40 people-times. Other than the small-size (4–6 students each course) hands-on training programs, the key factor of the success of the operation is in part due to the administration system that has been fully electronic-managed through the Internet. The e-management handles efficiently the user registration, equipment usage, financial accounting, manual documentation, and stock supply. The absolute equal access for all users has been enforced through the Internet-based user registration system. This hands-on MEMS training environment has also been proven successful and is strategically critical in providing key engineers to the rapidly rising MEMS foundry industries in Taiwan as mentioned above. Besides the training, the center supports a total of 68 professors for R&D activities. In addition to the achievements in RF-MEMS, and optical MEMS devices, the NTU BioMEMS team has developed the surface plasma resonance (SPR) technique that optically probes a near field bio-molecular layer with high sensitivity. Following the technology development, NSC suggests all three MEMS centers to be linked to the national nanotechnology project. To further strengthen its ties and to support the development on nanotechnology, NR-MEMSC has strategically migrated into NEMS with applications in communication, display, and bio-industries. The Core technology will focus on fundamental principles, measurement, manipulation, fabrication and devices in sub-micron to nano-scale, such as nano-probe, and nano-manipulation.

Taking notes of the NSC directives, the recently formed Nanotechnology Research Center at National Taiwan University (NTU-NRC) has taken the NR-MEMSC into its wing to further integrate expertise from faculties in college of Science, Engineering, Electrical Engineering and Computer Science, Medicine and Agriculture. The tasks of the center focus on the inter-disciplinary education program and integrated research projects. In February 2002, the nano-engineering curriculum has been officially offered in NTU with several other universities follow closely. A total of 92 undergraduate and graduate students enrolls for the NTU nano-engineering curriculum immediately after the opening of the curriculum. The plan of nano-science education program has also been completed within NTU and will be started in September 2002. Both programs emphasize effective science and engineering inter-disciplinary training. The research strength in nanotechnology at NTU includes more than 150 faculty members and specializes in molecular metal wire, nano-porous materials, nano-particles, quantum dot laser and infrared photo-detector, photonic crystals, spintronics, nano-bio, nano-positioning and manipulation, as well many system applications rooted from the vast and diverse domain knowledge generated from university long-term research activities. Several other universities are pursuing similar targets. With the successful model of the NTU-NRC, it has been said that for the first time in the history of National Taiwan University, faculties from different colleges have been able to be integrated at such a vast and fundamental level. The impact of nanotechnology as a core course at a leading university in Taiwan is worth noting. Taking the leading National Taiwan University as an example, it has traditionally considered Cultural Literacy and Linguistic Literacy as the two corner stones of core courses. However, with nanotechnology and biotechnology being regarded as the two technologies that will change the world in this century and now with S&T encompassing so many issues such as bio-ethics, societal impacts of new technologies, the university is now adding S&T Literacy (with emphasis on nanotechnology and biotechnology) and Information Technology (IT) Literacy (with emphasis on computer literacy at the most fundamental level) to its core courses. The addition actually reflects a significant departure of the old scenario where cultural training is needed for people with technological training but not vice versa. With these two additions, S&T is now being considered an important aspect to the general public knowledge bank. In other words, it tries to indicate that cultural, linguistic, S&T, and IT must be taught in a balanced manner to make sure citizens can function efficiently within this vast changing world. Hopefully, with the facelift of the core courses, the citizens of Taiwan can understand, support, or voice their concerns of various technological issues that drive this island country forward. With Taiwan now being a member of the World Trade Organization (WTO), the above changes facilitated by nanotechnology certainly have their global effects.

Conclusions

Inspired by the successful development experiences of its MEMS program, the establishment of core facilities and its sharing mechanism are being used as a means to foster close collaboration among the different sectors in Taiwan. With a paradigm 'a catalyst to change everything' for Taiwan's National Program on nanotechnology, nanotechnology is performing a facelift on every aspect in Taiwan ranging from education, industrial utilization, and to research and development. The force moving Taiwan's industry from manufacturing-oriented to a more balanced perspective based on research and development, manufacturing, marketing, intellectual properties, etc., will certainly have a long lasting impact on the daily life of the people not only in Taiwan but worldwide. Close international collaborations are definitely planned in Taiwan's nanotechnology program. With Taiwan moving forward along this path, it is believed that nanotechnology will no doubt become another focal point for Taiwan to interact with the world, both in science and in culture.

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