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Materials Science in the Developing World: Challenges and Perspectives for Africa**

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"Africans believe in something that is difficult to render in English. We call it ubuntu or botho. It means the essence of being human. You know when it is there and when it is absent. It speaks about humanness, gentleness, hospitality, putting yourself out on behalf of others, being vulnerable. It embraces compassion and roughness. It recognizes that my humanity is bound up in yours, for we can only be human together" (Desmond Tutu)

1. Introduction

"*Questions are never indiscreet, answers sometimes are*" (Oscar Wilde)

Materials — both very simple ones and composite or advanced ones — have always been important to human society, as shown by the fact that our prehistoric eras are named after the new material that defined them, e.g. the Stone Age, the Bronze Age, and the Iron Age.

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The present age is likely to remain known as the Advanced Materials or Nanomaterials Age. Capitalizing on the recent advent of new instrumentation for materials synthesis and characterization (including for example scanning probe microscopy techniques, which allow to visualize and modify surfaces at the atomic scale),[1] there has been a nearly explosive growth in materials science research, especially in the subfield known as nanoscience, which studies the properties of materials at the nanometer length scale.[2] Nanostructured materials are expected to provide society with radically new technologies, for instance to supply sustainable energy sources and vectors while protecting the environment as well as bring about significant advances in medicine.[3–5]

Within the last decade, nanoscience has become an emerging discipline with fundamental and applied components encompassing the physical, life, and earth sciences as well as engineering and materials science. An important aspect of nanoscience is that it bridges the crucial dimensional gap between the atomic and molecular scale of fundamental sciences and the microstructural scale of engineering and manufacturing. In this sense, it represents an opportunity to explore and link a vast amount of fundamental knowledge at the intersection of disciplines. The science of the ultrasmall is leading to new paradigms on the basic properties of materials; it is also expected to lead to the fabrication of novel high-technological devices in many fields of application from electronics to medicine. Because of its broad multidisciplinary scope this discipline is projected to increase the level of technological advance at a significantly higher rate than ever experienced in human history. As a result, the technical, educational, and societal implications of nanoscience are considered highly important, as attested by the major economic investment and the numerous national initiatives of developed and developing countries alike.[6]

The development of novel technologies almost always relies on the use of newly available materials. Such new technologies in turn are the basis for new industries, which create jobs and better living conditions. In this framework, when studying materials that may lead to innovative applications, the scientific community has the opportunity and even the responsibility to gear its work to the objective of improving the quality of life rather than just following scientific curiosity.

Today modern materials science is a vibrant, emerging scientific discipline at the forefront of physics, chemistry, engineering, biology, and medicine,[7] and is becoming increasingly international in scope as demonstrated by emerging international and intercontinental collaborations and exchanges. The international aspects of this growth are partly due to its effective structuring by the International Union of Materials Research Societies (IUMRS). The IUMRS has played a pivotal role in promoting materials research worldwide and has fostered the creation of many national/regional materials research societies throughout the world, including, in particular, the African MRS.

This Essay is divided in two parts. In the first section we describe the highlights of the MRS Africa 2007 conference, also making tentative suggestions for the next meeting, which will be held in West Africa (Nigeria, 2009). In the second section we look to the future in a more general sense and point out the most important challenges that we believe materials science should address today (both for developed and developing countries). Subsequently, possible research priorities aimed at identifying new strategies to bridge the current science and technology gap in areas that are critical for their

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development are suggested, specifically for African countries. We give special emphasis to recent success stories, such as the on-going NANOscience AFrican NETwork (NANOAFNET), which provides a comparative analysis (such as the standpoint of South African urban and rural universities) and an overall international perspective.

2. Highlights from the 2007 MRS-Africa

Following previous meetings in Morocco (2005), South Africa (2003), and Senegal (2002), the African Materials Research Society (AMRS) held its fourth biannual meeting on December 10–14, 2007 at a beautiful resort location overlooking the Indian Ocean (see Fig. 1) on the outskirts of Dar Es-Salaam (Tanzania). The conference was organized by the Eastern AMRS in collaboration with the College of Engineering and Technology (CoET), University of Dar Es-Salaam.

While focusing on the well-accepted materials research themes as in the second and third editions, the latest meeting evolved into an important opportunity for scientific communication, continental and international networking, and exchanges of ideas, also involving the participants of the International Conference on Nonconventional Materials (INOCMAT). Potentially this sort of event can also help to define priorities, challenges, and perspectives for materials research in developing countries, and comparatively for the whole world.

This theme was discussed in detail in the MRS Africa 2007 Keynote Address by Dr. Adriaan de Graaf, senior advisor at the U.S. National Science Foundation (NSF) Directorate for Mathematical and Physical Science (MPS). In particular, Dr. de Graaf described "The Materials World Network (MWN) and its Future Development".[8] The MWN is a program specifically created by the Division of Materials Research (DMR) Office of Special Programs (OSP) of the NSF to support international materials research and exchange of ideas, knowledge, and people. It has annual solicitations to fund cooperative activities in materials research between NSF and funding organizations abroad. To date, 14 African countries and the African Laser Center (ALC) in Pretoria (South Africa) have signed on to participate in this initiative. The program is part of a sustained effort by the NSF to provide resources to promote the development of a globally engaged workforce through the sustained support of international programs.

In accordance with its multidisciplinary character, the Dar Es-Salaam meeting featured materials research in a very broad sense, including not only the 'usual' content on advanced functional and nanostructured materials (composites, polymers, glasses, ceramics, metals, alloys, and oxides), materials characterization, electronic materials, and biomaterials, but also presentations on infrastructure materials, materials for environmental applications and water treatment, materials for catalysis and energy, materials recycling, materials for biomedical applications, and materials education. The conference attracted a wide international participation with delegates representing Algeria, Belgium, Botswana, Burundi, Cameroon, Canada, Congo, Egypt, Ethiopia, Germany, Ghana, India, Ireland, Japan, Kenya, Korea, Morocco, Namibia, the Netherlands, Nigeria, Norway, Pakistan, Russia, Rwanda, Senegal, South Africa, Spain, Tanzania, Tunisia, the USA, Uganda, Zambia, Zimbabwe, and for a total of 33 countries. Many members of the diasporas (scientific and nonscientific) of the continent, now living in Europe and North America, participated enthusiastically and are actively trying to establish exchanges and collaborations with local scientists.

Following a vigorous debate during an ad hoc session, the location of the next meeting in two years (i.e., in 2009) was determined, and the choice fell on Nigeria. This country represents in fact a good example of the central theme of the AMRS, since it is investing significant resources in Materials Research in general and in nanotechnology in particular. In this context, B. Babatope presented the status of advanced materials and nanotechnology research in Nigeria, whose government has established the Nigeria Nanotechnology Initiative since June 2006. This initiative has a desk at the National Agency for Science and Engineering Infrastructure (NASENI) led by Dr. A. Fasasi. While this initiative is quite broad, it does target several mainstream areas of research, the main ones being: *nanomedicine* (disease detection and treatment: cancer, malaria, tuberculosis, sickle cell anaemia; site specific therapeutics and diagnosis), *energy* (solar cells and OLEDs; plastic solar cells, organic electronics; amorphous and nanocrystalline Si films; high surface area nanostructures), *agriculture* (increase crop and animal yield; protection of seed from drought), *environment* (nanotechnology for water purification, provision of safe drinking water; clays are coated and used to filter and purify water), *information and communication technologies,* and *space technology*. As in the cases of the South African Nanotechnology Initiative (SANI) and the Moroccan Nanosciences Association (AMANAT) discussed later in this essay, the

Figure 1. The African Materials Research Society logo and view of the beach and the Indian ocean from the venue (White Sands hotel in Dar Es-Salaam, Tanzania) of the 4th International Conference of the African Materials Research Society.

general objective of the Nigerian initiative is to build capacity and train highly skilled personnel in these areas, which have been identified as priorities for the country's economic growth and prosperity. Admittedly, however, the ultimate purpose of the Nigerian Nanotechnology Initiative is to create wealth, in particular by bridging the technological divide and training new generations of scientists and engineers.

Through the active participation of its centers of excellence such as the USAMI (US Africa Materials Institute based at Princeton University, NJ) and the ICMR (International Centre for Materials Research based at the University California at Santa Barbara), the NSF was and is a leading supporter of the AMRS conferences and plans on continuing its efforts to sustain US/African collaborative research and educational programs. Generous funding from the ICMR[9] and USAMI[10] enabled significant participation from US academic institutions, both in terms of faculty and students. These two NSF-funded major materials research centers have been fostering collaborative research activities with a number of African countries that were represented at the 4th AMRS conference.

Various presentations highlighted success stories and direct outcomes of NSF-funded initiatives. In particular, USAMI director Prof. O. Soboyejo discussed some of the fundamental research and educational activities of his institute, which consist of: infrastructure materials for affordable housing, materials for lining the walls of furnaces and kilns that are used in the trillion-dollar metal melting industry, organic electronic materials for future light-emitting devices, solar cells, reliable small structures that are relevant to microelectronics, and micro-electromechanical devices. These projects incorporated the participation of scientists across the African continent including Egypt, Kenya, Nigeria, Senegal, South Africa, Zambia, and Zimbabwe.

The ground work for these collaborative initiatives has been laid out over the past few years by representatives of NSF and African countries since the first consultative meeting in Pretoria (August 2000). Dr. de Graaf emphasized that NSF seeks to continue to promote and support collaborative efforts on fundamental research and education between researchers at US institutions and African academic counterparts involved in joint projects. Various programs at NSF provide resources for fostering international research and educational collaboration activities; the International Materials Institutes, a program of the Division of Materials Research's OSP that funds USAMI and ICMR, is one of them.

3. Fostering Education and Research in Materials Science and Nanotechnology

Two parallel minisymposia on nanometer-scale science and nanostructured materials were held on Wednesday. One of the two, co-organized by G. Lisensky (Beloit College, WI) and T. Odom (Northwestern University, IL), was noteworthy because it focused on the burgeoning field of 'nanoeducation',[11,12] i.e., how to instruct most effectively to train practitioners of nanoscience and nanotechnology.

More specifically, Lisensky, Odom, and their instructors (E. Boatman from University of California, Berkeley and C. Sweeney from Northwestern University, IL) described how to design research courses for undergraduate students, based on inexpensive and easily accessible bench-top, nanometer-scale experiments that can be carried out with simple, good ideas and limited tools. One could use either bottom up approaches by spontaneous association of molecular building blocks,[13] or top-down techniques using compact discs as masters for soft lithography experiments.[14] Both approaches are cheap and affordable.

The tutorial lecture and practical session by Odom focused on the use of compact discs (CDs) as masters with repeated nanometer-scale features (Fig. 2). The CDs are used to produce nanometer-scale polymer structures on a variety of surfaces by emerging micro-/nanofabrication techniques such as replica molding, micromolding in capillaries, and micro-contact printing.[15,16] (CDs themselves are fabricated with such techniques).

In this case, both the fabrication and the characterization approach are 'low cost'; remarkably, a simple laser pointer is sufficient to determine whether the soft lithography experiments succeeded, by visualizing the diffraction pattern produced by the nanostructures.

Besides these 'hands-on' components, the courses focus on developing analytical skills and fostering creativity, including writing frequent reports, discussing subject matter orally, and more importantly, set up innovative research proposals and even prepare business plans for students who have entrepreneurial talents and interests. These proposals are then evaluated critically by internal peer review in the classroom and finally the research projects are executed in small groups.

It is worth noting that symposia focusing on materials education have become highly popular at Materials Research Society meetings, not only in the USA but also internationally in the framework of IUMRS conferences (e.g., at ICMAT meetings in Singapore[17] and at ICEM 2008 in Sydney,

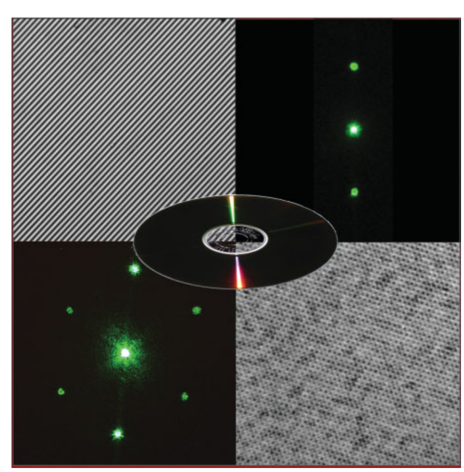

Figure 2. Bench-top nanofabrication using a Compact Disk as master. Reproduced with permission from [14]. Copyright 2007, ACS.

Australia[18]). In view of all this, and since the students of today are the scientists of tomorrow, the next edition of AMRS to be held in Nigeria in 2009 should consider organizing a symposium on materials science education as one of its parallel sessions or perhaps even as a separate school to be held as a satellite two-day event after the main conference, if sufficient resources are available. Other specific suggestions to consider for the next edition of the AMRS include: (a) finalizing and publishing the conference program well in advance so that prospective participants can make adequate plans, and (b) ensuring a greater involvement of vendors of scientific equipment, by organizing an exhibit and also by holding ad hoc instrumental sessions that would have an intrinsic educational value.

Another successful event held during the AMRS 2007 was the USA–Africa symposium on hybrid inorganic/organic and nanostructured materials organized by Prof. A. Lachgar from Wake Forest University, NC and entirely funded by the ICMR. The first edition of this symposium was held at the Third International conference of the MRS Africa held in Marrakesh, December 7–10, 2005. It brought together a total of 24 participants from Africa (Morocco, Algeria, Senegal, and South Africa), Europe (France, Germany, and Spain) and the US. It was funded through a supplement to Prof. Lachgar's NSF grant and the ICMR. The recent follow-up event in Dar Es-Salaam featured 23 participants from four continents: Africa (Morocco, South Africa, and Tanzania), America (US and Canada), Asia (South Korea and Japan), and Europe (France, Spain, and UK). The sessions were very well attended and the topics and results presented as well as the scientific discussions, exchanges of ideas, and future prospects were at the forefront of fundamental research in inorganic and organic materials chemistry.

4. The Abdus Salam International Center for Theoretical Physics (ICTP) and its Legacy

To our knowledge, the ICTP (Fig. 3)[19] in Trieste (Italy), which was founded in 1964 by the late Nobel Laureate in Physics Abdus Salam,[20] was the very first international organization to address the scientific and educational gap between developed and developing countries. Partly to avoid capital cost in its work the emphasis was placed specifically in fields where expensive equipment is not required, namely theoretical physics and mathematics. Over the last half century the ICTP has trained thousands of students and scientists from both developed and developing countries, providing a forum for regular North/South scientific exchanges. This institution has recognized the present, urgent need to promote and advance science (both in terms of education and of research) in developing countries,[21] particularly by helping scientists from the South overcome their isolation.[22]

The role of the ICTP in the history of science in the second half of the 20th century cannot be overemphasized. During the cold war, the ICTP was one of very few places where scientists from the East and West could meet in person and exchange ideas freely. It has organized and supported a great number of schools and conferences both in Trieste and abroad; in particular, it has established a very strong presence in Africa,[23] also creating a network of associated institutions throughout the continent.

Figure 3. The Abdus Salam ICTP (front view). Reproduced with permission. Copyright 1999, ICTP. Copyright: Massimo Silvano, ICTP Photo Archives

However, since most of the people involved stayed in these rather academic fields the economic impact of this effort has been somewhat limited. With choices tailored to make their impact in fields which are scientifically *and* technologically relevant to the developing countries involved, the ICMR and USAMI (discussed above) and the African Institute for Mathematical Sciences (AIMS)[24] and the Sustainable Sciences Institute (SSI)[25] described later in this Essay are some of the most distinguished institutions that follow directly or indirectly in the footsteps of the ICTP and build on Salam's legacy. Indeed, setting up such organizations in both the North and the South is a very promising approach towards bridging the knowledge and technology gap between developing and developed countries, also with the view of creating economic opportunities based on technological advances.

5. Examples of African Country-Specific Success Stories in Research

We mention here three remarkable examples of African countries at geographically complete opposites of the continent whose research establishment is to be considered overall successful and that therefore deserve special attention: Morocco, Tunisia, and South Africa.

The Moroccan nanotechnology association was created under the auspices of the Hassan II academy of sciences. The so-called AMANAT is an official forum intended to enhance the status of nanoscience research in Morocco involving a national dynamic as well as an international networking activity channeled through the Moroccan scientific diaspora[26] such as Prof. M. Boussmina from Laval University (Quebec City, Canada). To foster comprehensive nanoscience projects within the national landscape, AMANAT has organized the 1st Moroccan Days of Nanoscience and Nanotechnology (8–10 April 2007) in one of the leading national universities, the University of Al Akhawayn in Ifrane under the leadership of S. Zouhir. In the same perspective, Morocco has implemented a series of national centers for materials science such as the one located at the University of Fez, where world class nanoequipment has been implemented.[27] The stirring synergy in North Africa has led to the creation of a regional North African network in materials science in general and nanoscience specifically. The 1st USA–North Africa Regional Workshop on Nanostructured Materials and Nanotechnology was organized purposely to promote networking in this region.[28]

Tunisia's economy and scientific research are heavily financed by the Gulf Countries, and this country has identified biotechnology as a priority area of research; indeed, the Institut Pasteur[29] in Tunis is famous worldwide for its research on the study of infectious diseases caused by insect bites and reservoir animals. Since the beginning of the 20th century, the Institut Pasteur has built on the legacy of Dr. Charles Nicolle (Nobel laureate in Medicine in 1928 for his research on typhus fever and brucellosis), playing a leading scientific role in the control of various parasites (malaria and leishmaniosis among many others) in Africa.

In 1991, the government of Tunisia created an ad hoc secretariat, whose mission is to promote scientific research and technology and to coordinate and evaluate national research activities.[30] This represented a very important milestone that helped structure the R&D landscape of this country. The secretariat works closely with other ministries to formulate national plans and policies for science and technology. Other important government branches that support research in Tunisia are the Higher Council for Scientific Research and Technology, which is headed by the Prime Minister and suggests policy options for R&D, and the Ministry of Higher Education, Scientific Research and Technology, which coordinates academic research in the country through its General Director for Scientific Research and Technology. The Tunisian higher education system is composed of 85 university-level institutions, comprising 208 research laboratories in scientific and technical fields. Other ministries have implemented research institutions oriented towards their field of interest, which include agriculture, health (largely at university hospitals), and science and technology.

Building on these initiatives, Tunisia has begun developing a forward-thinking strategy for its scientific and economic development, recognizing the importance of knowledge creation in today's modern society. The progress achieved by this country is now widely recognized. Tunisia is currently ranked among the most dynamic users of new technologies along with China, Brazil, and South Africa.[31] In the 2005 World Economic Forum Report in Davos, Tunisia was ranked 31st out of 104 countries considered as the most advanced in the ICT sector. In 2006, Tunisia was ranked as the first African and Arab country by the Davos World Economic Forum Report in terms of global competitiveness of its economy.

South Africa is rich in natural resources and can therefore afford to invest in relatively broad and high-risk research programs through its National Research Foundation (NRF), which funds both government laboratories (e.g., iThemba Laboratory for Accelerator-Based Science (LABS),[32] which is one of the country's six national facilities) and individual or groups of principal investigators based in South African academia. More recently, the South African Council for Scientific and Industrial Research (CSIR), which was originally aligned with private-sector funding, has begun to reorient itself towards basic research activities[33] in materials science in general and nanoscience in particular. Today, the development of a high quality education system and a broad research culture are considered the foundations of this country's progress towards democracy and sustainability. Besides the role of basic science in creating a society geared to the search for truth, applied science will enhance the ability to innovate, without which the country would constantly depend on foreign technologies, know how, and general inputs. In the aftermath of the democratization process, South Africa has aimed at internationalizing its scientific community, signing bilateral agreements with most of the major Western countries as well as with China, India, Japan, and Russia, building on the conviction that science can bring people from different cultures together to work on common goals and problems. In so doing, South Africa has significantly increased its exchange of scholars, developing new kinds of relationships and role models for students, thus also succeeding in enhancing its ability to deliver competitive research and education and graduate highly skilled students. Considered as a continental driving force in science and technology (S&T), South Africa has recently invested heavily in research. Under the leadership of a visionary team led by its minister Dr. M. Mangena and its director general Dr. P. Mjwara, mathematician and physicist by training, respectively, the Department of Science & Technology of South Africa has been massively devoted to several initiatives with a materials science focus. Advanced Manufacturing Technology Strategy (AMTS) was among the backbones of such a vision.[34]

Within the AMTS, SANI was launched in 2006 with a full sponsorship of about 45 M€ over three years (2006–08). Two nanoscience centers located in the Gauteng region were launched in 2007. In addition, three flagship projects managed by the South African NRF were initiated at the end of 2007.[35] Likewise, two centers of excellence in materials science in catalysis and hard materials were inaugurated in early 2006 involving several high education institutions and industries in addition to several prestigious chair professorships at participating South African universities.

6. NANOAFNET-iThemba LABS: a Dynamic African (Nano)driving Force

In addition to the Africa chapter of the materials research society (AMRS) mentioned above, within the continental landscape the African materials community has launched the aforementioned NANOAFNET.[36] As a complementary network component to both the AMRS and the ALC, NANOAFNET has promoted awareness throughout the continent and established a real synergy involving numerous senior and junior scientists from more than 27 African countries (Fig. 4). This official African network in nanotechnology supported by the Abdus Salam ICTP, the International Council for Science (ICSU), the International Union of Pure and Applied Physics (IUPAP), US-NSF, the Third World Academy of Science (TWAS), and the African Academy of Science (AAS) among others, has its headquarters at iThemba LABS.

NANOAFNET is strategically structured with 4 regional coordinators and 27 national contact points with additional partners in North America, Europe, Middle East, and India as well as an international advisory committee with its council chaired by Dr. M. Maaza, the initiator of the South African Nanotechnology Initiative (SANi).[37]

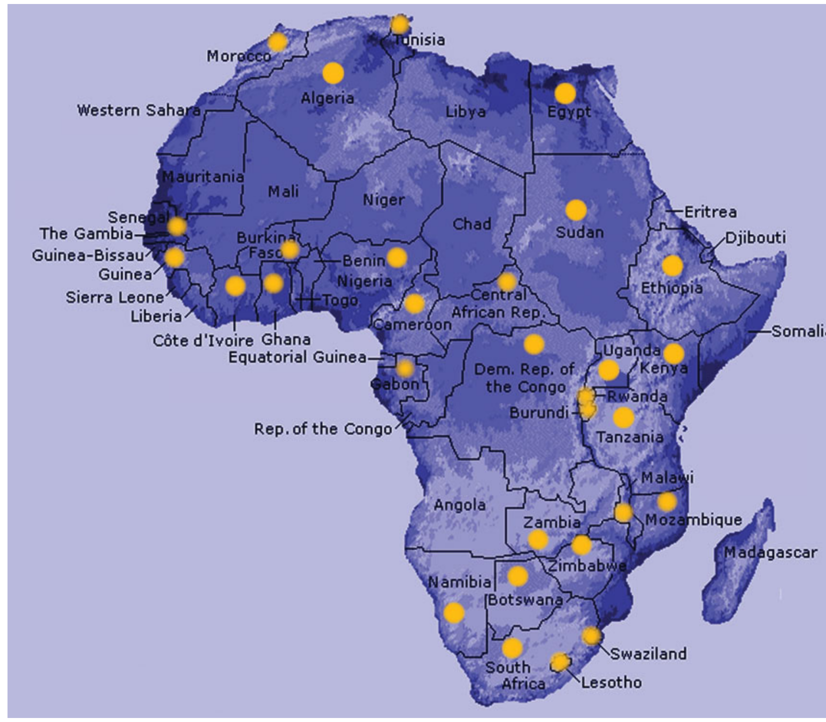

Figure 4. NANOAFNET participating countries.

Being located within the premises of a national facility in South Africa, its members have access to a set of world class research services for the synthesis and characterization of nanomaterials. In addition, members of the network can draw on the resources available within the region and nationally in South Africa as well as continentally, as they agree to pool their capabilities and facilities for common use.

NANOAFNET has developed two main research programs: (i) fundamental nanoscience and capacity building and (ii) nanophotonics for renewable energy and photonics applications. Currently, the ongoing projects that underpin these two broad programs are:

(i) Fundamental nanoscience and capacity building thrust

- Fast-spectroscopy plasma studies of laser-ablated nickelate nanostructures
- Magneto-optical properties of quantum dots and size effects
- Mott's phase transition and novel tunable/reversible ultrafast nanoplasmonics
- Anderson localization phenomena in carbon nanotubes
- Surface atomic ordering, size-induced phase transitions in metallic nanoliquids
- Self-assembly of C_{60} molecules and C_{60} nanorods engineering
- Nanostructured diamond-like carbon by pulsed laser ablation
- Confinement of porphyrins in nafion matrices for solid χ^3 optical applications

(ii) nanophotonics for renewable energy and related photonics applications

- Vanadium dioxide-based nano-thermochromics for active infrared modulation
- Molecular recognition within porphyrins nanorods and their integration in solar cells applications
- Nanostructured transparent conducting oxides of undoped/doped ZnO for transparent electrodes applications in dye solar cells
- Engineering of WO_{3-x} nanorods for electrochromic and hydrogen sensing applications
- Cost-effective low P-T engineering of nanometer-scaled TiO_2 for dye solar cells applications
- Nanostructured tubular Fe_2O_3 and their application for water splitting and hydrogen sensing

NANOAFNET has implemented its major postgraduate training program funneling the major component of its funding received from the Abdus Salam ICTP and matching funds contributions from the ALC, the South African Department of Science & Technology, the South African NRF, iThemba LABS, the South African Pebble Bed Modular Reactor (PBMR)[38] program and the US NSF. The network is currently training 16 junior scientists from seven different African countries (Algeria, Cameroon, Ethiopia, Morocco, Nigeria, Senegal, and South Africa) at the MSc and PhD level, whereby the sponsored visits are about 3–6 months up to one year. In terms of senior scientist mobility, it has implemented its second program in 2006. Using its matching fund strategy, 12 senior scientists from nine different countries (Algeria, Cameroon, Egypt, Ethiopia, India, Lesotho, Morocco, Oman, and Zambia) were supported for short term visits (from 1 to 3 months). Its mission has entailed to its senior and junior fellows to ensure publication of results in peer reviewed international journals with relatively good impact factor (*Applied Surface Science, Solar Energy Materials and Solar Cells, Solid State Communications, Optical Materials, Thin Solid Films, Journal of Alloys and Compounds, Optics Communications, Sensors and Actuators B*).

Aiming to enhance the visibility of the African continent in nanoscience-related research, thanks to its dedication to excellence in science and education, NANOAFNET has achieved global recognition by receiving international awards. Among these, we mention the following: (i) Global School for Advanced Studies Award by the Taiwan Department of Science and Technology, (ii) the Global Nanotechnology Network Award by Tsinghua University and Industrial Technology Research Institute, (iii) Great Minds of the 21st Century in Nanosciences award by the US ABI Inc., (iv) the outstanding scientists of the 21st century in Nanophotonics award by the Cambridge IBC in addition to three Cum Laude degrees. Its members have been invited to present this continental synergy at several international conferences and workshops in Central America, Europe, Asia, Middle-East, and Africa, where plenary and/or invited contributions were delivered. Moreover, to enhance both the continental and international collaborative synergy in nanoscience, this network was instrumental in co-organizing scientific international conferences, schools, and workshops at its headquarters at iThemba LABS in Cape Town. It has encouraged participation from the African continent through the possibility of full financial support for outstanding participants from disadvantaged parts of Africa as well as from abroad. So far during the 2006-07 period, one international conference, two workshops and one college event were co-organized with the Abdus Salam ICTP and the US-NSF among others with delegates ranging from 70 to 210 and African participation between 60 and 85%.

Finally, to keep the momentum and increase the visibility of African research in nanoscience, a special issue dedicated to nanoscience in Africa is currently being prepared for publication in the *International Journal of Nanotechnology* (similar topical issues were released for Spain in 2005, Ukraine and Korea in 2006, China and Singapore in 2007, and Australia, France, and Canada in 2008).[39]

7. Perspectives from a Rural (South African) University

Discussion with Prof. M. Ndwandwe (University of Zululand, South Africa) led to the following observations. South Africa's higher education institutions can be divided into two broad categories: rural universities and urban universities. This classification is not simply related to geographical location but rather an artifact caused by the history of the country. The urban universities were built for the upper class whereas the rural universities were meant for the other classes. The latter are better resourced in terms of research equipment and human capital when compared to rural institutions; rural institutions tend to draw their students from rural communities, which are usually much poorer than urban areas. These students are less prepared for university due to the school system they have had access to (rural schools are generally poorer). Rural universities have devised ways to make the best of their student clientele. These students then tend to transfer to urban universities once they have completed their first degree (this largely occurs due to the lack of infrastructure at rural universities). These problems are well known and in principle should be solvable with adequate financial support; however, funding is scarce and competitive for both types of institutions. Can one develop strategies that can alleviate the situation for rural universities (or at least bring them up to par with their urban counterparts)? What strategies can rural universities adopt used to cope with the plight they find themselves in?

We propose three possible, simple strategies (by no means exhaustive) to address the situation, each involving some form of collaborative pursuit: (i) collaboration with national laboratories, (ii) partnership with other universities, and (iii) collaboration with industry.

South Africa has several research centers (iThemba LABS, located south of the country in the Western Cape, Astronomical Observatory located in the Karoo, Sutherland, etc.). For a South African academic institution intending to initiate a research program with almost nothing in terms of infrastructure, collaborating with national facilities probably represents the best option. Such facilities host well-equipped laboratories (especially relative to the ones available at rural universities) as well as technicians to keep the instruments functioning properly and are staffed by qualified scientists who can co-supervise graduate students. Faculty members from rural institutions and their students also have the opportunity to meet and interact with national lab internal scientists. These scientists occasionally visit the rural institutions, where they give talks and interact with more people. Wherever the lack of infrastructure is severe, experiments cannot be carried out in loco, thus limiting the usefulness of the visit. Most national laboratories are also located far from rural institutions ($\sim$2 000 km). As a result, in most cases faculty members can only perform their research during teaching breaks and vacation periods. The time available for equipment use is therefore limited, leading to comparatively low research outputs. In a country where everybody is assumed to be equal and research funds are allocated on the basis of scientific output, rural faculty members find themselves at a significant disadvantage. Therefore, although collaborating with national laboratories can be helpful to a certain extent, the best solution is to invest in infrastructure at rural institutions so as to be at least on par with the capabilities of urban institutions.

Some rural institutions collaborate with urban universities that are usually better equipped. Several of the latter welcome these initiatives while others are not open to partnership. Such collaborations are always unequal relations and therefore hardly ever work well. In addition, institutions compete for the best students and staff, the great majority of these being attracted essentially by default to the urban institutions. Some attitudes are also not easy to change. For instance, when raised in a context that encourages "looking down" on others, an attitude of presumed superiority is difficult to eradicate and therefore persists. Also this possibility therefore leads to the conclusion that rural institutions need to implement their own infrastructure, if they harbor any hope to climb up in the academic ranking system and become competitive in attracting talented students and staff. If they do not succeed in doing so, their role will be more similar to advanced high school systems rather than real universities (i.e. advanced in terms of learning, but not at the forefront in creating new knowledge by doing original research).

The third option is to work closely with industry. Some companies and semigovernment entities in South Africa host well-equipped laboratories for materials synthesis and characterization. Carrying out projects in collaboration with industry often has the added benefit of performing research that is relevant for the country (and possibly the continent). University graduates need to acquire skills that will help them to find employment easily. In certain cases, industrial scientists are willing to co-supervise graduate students (thus providing an additional advantage to rural institutions); these cases are fairly rare, since student supervision may take away valuable time from the company's employees, causing a reduced productivity. Moreover, private companies are interested in developing and selling their products for a profit, rather than scientific publishing and in some of the cases they want to keep the results of the research secret so as to preserve their competitive advantage. Universities on the other hand want to disseminate the results of their work through peer reviewed publications and advertise as broadly as possible the new knowledge they have created and their accomplishments. Furthermore, most South African industries are not particularly developed, the main industry being mining. Lastly, old habits die hard. Most of the educated people presently working in South African industry originally obtained their higher education at urban institutions and still tend to nurture these old links rather than develop new collaborations with institutions that are not highly ranked. Ultimately also this third possible strategy points to the fact that rural institutions require their own infrastructure for medium and long term development.

Some industries in South Africa are relatively rich (e.g., De Beers diamond mining and processing, Sasol chemicals and fuels, South African breweries, etc.), to the point that they can afford to discard obsolete yet still usable research equipment. The tendency is to donate such equipment to urban universities; this is not surprising as these have been working closely with industry for many years. Some of this equipment can still be used to obtain new publishable results (even though it can take weeks to achieve results that can be generated in just a few hours on a new instrument). Donated equipment can also be used to train students. Rural institutions could therefore take up some of this second hand infrastructure (depending on the goodwill and willingness of local industry). The issue of qualified technicians at rural institutions is also somewhat challenging, so that if rural universities were to receive such donations, they might not have adequate resources for their operation.

The idea of donating/recycling old yet still functioning equipment merits further consideration, yet in a broader context. Many laboratories in developed countries have excess equipment and tend to discard old models in favor of newer ones, partly because of the periodic availability of new products, and partly because research equipment is similar to automobiles: after about 10 years it has served its purpose and it is time to upgrade or change to a new model altogether. What if the international research community (maybe even a multinational corporation), instead of discarding and destroying some of its old equipment, would simply donate it to higher education institutions in developing countries, for example rural institutions in South Africa? To achieve this, the local government in the receiving countries could form nonprofit organizations (equivalent to funding agencies), whose role would be to collect the equipment to be donated, repair it (if necessary) and then loan it to higher education institutions on a competitive basis to evaluate real needs and the originality of the research to be performed with a given system (for example with stringent clauses forbidding subsequent sale). The receiving institution could be provided with well-trained technicians for installation, operation, and maintenance, with the assistance of the donor and the local nonprofit organization. After placing the equipment at a given institution, progress should be periodically monitored. If the equipment is not well used and the resulting research output is low over a reasonable period of time, then it should be removed and relocated elsewhere on the basis of merit, ensuring accountability. Further it would be expected that with the results obtained these scientists should also be able to compete for other resources (e.g., more equipment and salaries for manpower) and for publication on par with others. The drawback of course is that used equipment tends to require more in terms of maintenance and operating costs (just like used automotive vehicles).

These are some of the strategies currently employed at rural institutions in South Africa, to improve their local infrastructure and resources, as they are constantly looking for new ideas and opportunities to become more competitive. Investing in advanced training programs in such institutions and in universities in developing countries in general should be part of a more general strategy to bridge the current divide between rich and poor, bearing in mind that scientific research and higher education are meant for the benefit and advancement of humanity.

8. Economic Tools and Approaches for the Development of Research in Africa

Having looked quite closely at the specific case of South Africa and its recent science and technology strategy, we now try to expand the discussion to the whole continent,[40,41] attempting to give a broader (though non-exhaustive) view of challenges, opportunities, and (in the subsequent section) potential priorities.[42,43]

Urgent steps must be taken *now* to commence bridging the widening knowledge and technology gap that exists between developing and developed countries,[44] which is also the cause of unequal distribution of resources, in particular with respect to energy use,[45] between North and South, at least in part.

Figure 5[46] displays a photographic composition of the world taken from satellites, showing the much higher use of electrical lighting in rich countries in comparison to developing countries.[47] Bridging this gap will be challenging and will take at least one, if not more, generational effort. It will entail a concerted 'bottom-up' scientific approach whereby scientists spontaneously develop north–south collaborations and promote exchanges based on mutual interests, combined with 'top-down' political support involving significant government investment.

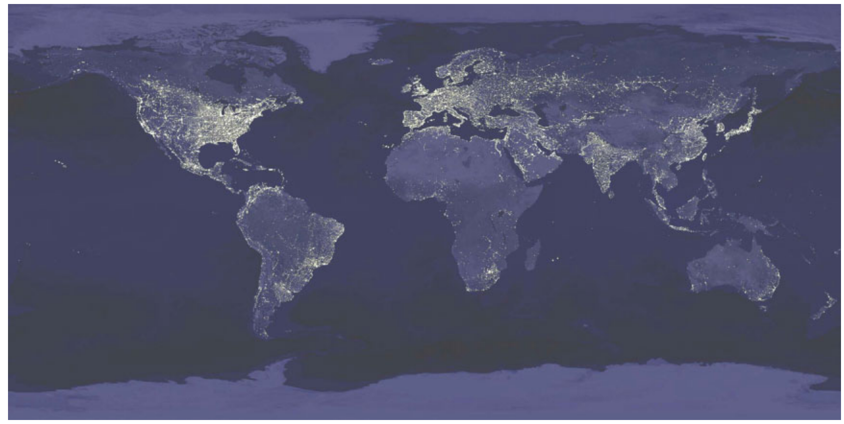

Figure 5. The world at night from composite satellite imaging. Image and Data processing by NOAA's National Geophysical Data Center. DMSP data collected by the US Air Force Weather Agency.[45]

Most of all, it requires that we accept to learn from each other, rather than perpetuating an arrogant, patronizing, and condescending view that rich countries should 'help' developing countries, the real question being, how can we help each other to develop a sustainable world?

What is perhaps striking is that the most important and urgent challenges faced by developing countries are the same ones of society as a whole: improving health, access to clean and renewable energies, preserving and protecting the environment. Sustainability (intended in a broad sense) is indeed the keyword here. Rich societies continue to overexploit the planet's resources, which have now become very scarce, with the threat of collapse.[48] They should rather relearn the long forgotten concept of sustainability that our ancestors had developed at the time of rural/agricultural societies, prior to the industrial revolution, and that are still widely used in developing countries. In this respect, bridging the gap that we mentioned is clearly a two-way process of mutual learning and understanding.

We are convinced that this approach in turn requires more scientific research and the development of new technologies, particularly new materials. In this sense, developments and breakthroughs in materials science hold the promise of addressing and perhaps solving these challenges, thus ensuring humanity's future prosperity, both in developed and in developing countries. In certain cases medium-term solutions that help rural communities to develop their facilities and infrastructure and be in touch with distant urban communities could be a good starting point (e.g., implementing solar power for wireless and satellite communications).

We realize that the countries belonging to the so-called 'bottom billion'[49] have more urgent priorities (e.g., feed their people or even cease wars or civil wars) that are incompatible with initiating even basic scientific research programs. Nevertheless, what we are suggesting here may be useful to those countries once they have succeeded in emerging from their conditions of extreme poverty.

Despite many collaborative North–South efforts presently under way, in our view, two main issues presently hinder the fostering of advanced research initiatives in developing countries, namely, (i) the lack of suitable equipment and infrastructure (which requires capital investments of the order of hundreds of millions of dollars) and (ii) the brain drain, i.e., the departure of bright young minds towards rich countries that nurture their education, luring them with the prospect of riches and glory.[50] In fact, most southern societies face common problems in terms of high levels of poverty and unemployment, and the need for drinkable water, sanitation and health facilities, and infrastructure; they also have to cope with the continuous loss of skilled workers towards richer northern societies.

With respect to (i), it can easily be argued that there is no need for every single country to acquire infrastructure that is costly both in terms of initial acquisition and subsequent maintenance and operation. Certain approaches for materials synthesis and modification are fairly simple and low cost and can be easily implemented with relatively minor initial investment.[51–53] Subsequent material characterization using advanced techniques can be carried out remotely through international collaborations. At the same time, once well-defined priorities are identified, several countries can develop collaborative initiatives, for example establishing regional centers that will host the necessary equipment in such a way as to serve a whole region and basin of users. In other words, resources should be pooled for common use by neighboring countries rather than dispersed and underutilized. At the same time, other specialized equipment can be accessed by developing ad hoc collaborations with developed countries. With respect to (ii), we emphasize that the brain drain can be prevented and to some extent reversed only by creating significant competitive opportunities at home. We mention for example the NRF research chairs scheme in South Africa,[54] whose objective (similarly to the Canada Research Chairs program[55] in Canada and the Federation Fellowships program[56] in Australia) is to recognize locally developed excellence and reclaim to the country talented scientists who have left to work overseas.

9. Identifying priorities

Most developing countries cannot afford to invest in broad research programs of the kind undertaken by advanced countries. Indeed, some countries are so poor that they cannot invest in research at all. On the contrary, to bridge the technological gaps they currently face they are virtually obliged to set well-defined priorities related to their basic, short term needs. At the same time, their research activities should not be too narrow in scope, or their choices will negatively affect the education of the new generations of scientists. In other words they cannot afford to spread themselves too thin by investing broadly, nor can they risk investing too narrowly and exclusively or they will not have the specialists needed to advance and deploy key technologies that will help them grow in the medium and long term.

Examples of immediate priorities that are likely to be selected by many developing countries, especially in the southern hemisphere, are renewable and sustainable energy sources (e.g., photovoltaics since sunshine is abundant in Africa, South America, and South East Asia) and new technologies for water purification (for example, nanofiltration membranes made of a variety of nanomaterials[57]). It could be argued that the real applications of nanoscience may be decades away, and therefore for developing countries with limited resources it might be risky or premature to invest in this type of research today. On the other hand, although 'nanotechnology' is not yet necessary to replace current technologies whose functioning is overall adequate, rich countries will be pouring a lot of development into these systems motivated by the aim of increasing sustainability as much and as fast as possible. As these improved systems become available, developing countries will need their own experts in these fields. Now is the time to begin research efforts such as training centers and incubators. The research component in all this is essential to keep the best from staying in the rich countries for better living conditions.

In this context, we tentatively suggest a certain number of possible general 'action items', as follows:

(1) Identify national priorities and allocate resources accordingly (when a given country is poor and resources are not sufficient for a broad investment in research), creating funding agencies whose mission is to support scientific and technological research in well-defined areas, ensuring that resources are allocated to the best scientists on the basis of merit, track record, and accountability. Improving public health, renewable and sustainable energy, and clean water are likely to be at the top of the priority list for most developing countries. Although economic growth is regarded as the best approach to escape poverty, that escape can be attained more rapidly by improving public health, as pointed out by H. Rosling from the Karolinska Institute in Stockholm, Sweden.[58] Therefore techniques that leverage this aspect appeal directly to both humanitarian motives and to development for the future. We remark that water shortages, water contamination, and lack of proper sanitation presently represent the greatest health problem worldwide, causing the death of about 4500 children every day.[59] Any improvements in the techniques for combating these ills are natural targets for the efforts we propose here.

(2) Set up international advisory boards for major governmental funding agencies. Board membership should be broad (with representatives from academia, national laboratories, and industry) and balanced, including local scientists as well as scientists from abroad. The board should also help identify research priorities, set goals, and evaluate results for both basic and applied research and would be responsible for establishing ethical and peer review guidelines. Such a board will be invaluable in strengthening the rationales and arguments for obtaining support and for running the projects in a productive and useful way.

(3) Prevent any possible wrongdoing from university and governmental research. For international credibility with respect to external funding, the peer evaluation of the quality of the research and of the people doing it must be completely assessed on the basis of merit. This should serve as an example of the rewards of removing influence and corruption from a system and thus provide a timely model for other sectors of society (for example, by implementing zero-tolerance policies with respect to illicit, corrupt, and unethical behavior with severe and swift consequences for transgression). This should be done by introducing competitive and rigorous peer review systems and stringent research ethics guidelines that are to be continuously monitored by international advisory boards. The dangers of not recognizing merit in research through transparent competitions, even in rich countries, cannot be overemphasized.[60,61]

(4) Focus on education as a way of empowering people through their advanced instruction and training as the future generations of scientists, engineers, and entrepreneurs. There is ample empirical evidence that developing countries whose economies depend heavily on exporting commodities (minerals in particular) but which do not at the same time develop their people's skills beyond primitive resource extraction have slower growth rates and higher income inequality levels than comparable countries that lack natural resources;[62] this is commonly referred to as 'the resources curse'. In fact, as demonstrated by South Korea (which was the poorest country in the world just half a century ago), a country's people are its best resource[63] and can richly repay investment in their development. In

the space of a few decades this country developed at an astonishing rate, passing from being the developing backwater of Asia to the 12th largest economy in the world.

(5) Capitalize on success stories from Africa and try to follow examples from highly successful Asian countries such as South Korea, Taiwan, Hong Kong, and Singapore, which have demonstrated astonishing and sustained development rates over only few decades. Such success stories are simply to be intended as a message of hope, as we are fully aware that development models cannot be trivially exported between different cultures or geographical contexts.[49]

10. Increasing the Opportunities In- and Out-Of-Africa

Recently, the Council of Science Editors (CSE) organized a global theme issue on poverty and human development, in which scientific journals throughout the world simultaneously published articles on this topic of worldwide interest on October 22, 2007.[64] The goal of the CSE global theme issue is to stimulate interest and research in poverty and human development and disseminate the results of this type of research as widely as possible. This is an international collaboration of 235 journals from both developed and developing countries (the journals involved are mostly related to medical research and nursing, but also include the *Nature* publishing group and *Science* magazine).

In particular, the journal *Nature Materials* highlighted the above mentioned AIMS through an Editorial[65] and a Commentary.[24] This recently born institution offers a very broad nine-month post-graduate course, aiming at enhancing the students' mathematical abilities while providing them with an overview of modern science. Van den Brink and Snyman, who visited AIMS as lecturer and tutor respectively, remark that the institute focuses on excellence as well as on Africa's specific needs. Since one of the great challenges for the scientific community is to bridge the gap between north and south, they highlight the potential role of AIMS as a model for similar organizations operating in physics and materials science.[24] They also argue that its location and pan-African student population strongly encourage a commitment to the continent, which desperately needs a new generation of academics and scientists in general.

The SSI and its activities were highlighted by *Nature Chemical Biology*.[66] This institution, founded by E. Harris in San Francisco, provides instruction on a variety of topics in biology and the health sciences. This is achieved through the organization of workshops, whose objective is to provide technical skills that are relevant to local needs in developing countries and that can be rapidly implemented, as was the case when Harris improvised a course on molecular biology during her volunteer work in revolution-torn Nicaragua.[66]

Nature Nanotechnology, on the other hand addressed how Nanotechnology can help develop devices for water purification[67] as well as for early disease detection and in optimizing the use of other natural resources. As we have mentioned above, water purification should be considered a high priority as the access to clean water has a huge impact on public health and consequently on development.

It is thought that by developing suitable nanostructured materials,[3,4] nanotechnology can contribute to five[68] of the eight highly ambitious Millennium Development Goals (MDGs) set by the United Nations in 2000,[69,70] namely (i) eradicate extreme poverty and hunger, (ii) reduce child mortality, (iii) improve maternal health, (iv) combat HIV/AIDS, malaria and other diseases and (v) ensure environmental sustainability. The other three objectives, (vi) achieving universal primary education, (vii) promote gender equality and (viii) develop a global partnership for development can and should be tackled by promoting science and education at all levels. Indeed, fostering science is a way of investing in the future, and as such it is at least as critical for developing economies as it is for the wealthy nations;[71] in fact, at least half of the MDGs are issues that also affect society in developed countries.[37] Promoting education and the importance of science and technology can be significantly boosted by projects such as the One Laptop Per Child, which is a plan by N. Negroponte to equip children in developing nations with a '100 $ laptop'.[72]

11. Conclusions and Perspectives: International Materials Research and Education Centers in Africa

It is overall difficult to predict whether nanotechnology can really make a difference in improving people's quality of life both in developed and developing countries. Nevertheless, it is clear that materials science in general has been able to fulfill such a role (arguably since prehistoric times) and can continue to do so, at least in part because of its multidisciplinary approach. To sum up, materials science (and particularly nanotechnology and nanomaterials) is exhibiting explosive growth and in which excellent work can be done with ingenious ideas that do not necessarily require access to highly expensive equipment. Hence, these two areas are ones in which a significant contribution can be made with relatively modest means to the development of African technology and economic growth. Thus, investing in materials research and education should be an important priority for developing countries wishing to take action to bridge the knowledge and technology gap and to implement long term educational activities to train their future generations of scientists and engineers. This realization calls for much grater investment and funding to ensure effective North/South and East/West networking and exchanges to maximize opportunities for all.

While drafting this manuscript, two new major initiatives for materials research and education in Africa, for the establishment of international nanotechnology centers for Africa were launched. First, following the initiation of the AMRS in Dakar

(Senegal) in 2002, the ALC in Johannesburg (South-Africa) in 2003, and the NANOAFNET in Trieste (Italy) in 2004, and their very successful implementation, Prof. A.C. Beye, founding Chairman of the AMRS, founding member and present CEO of the African Laser Center (ALC), and founding vice-chairman of the NANOAFNET together with its chairman Dr M. Maaza (iThemba LABS), are in the process of establishing a centre for materials, lasers, and nanometer-scale science, engineering, and technology in Africa. Initial funding of 10 M$ US has been approved to build the first laboratory for advanced infrastructure and instrumentation to be located in West Africa (Dakar, Senegal). This laboratory will be set-up for modeling, simulation, fabrication and characterization of bulk, thin-film and nanostructured materials and systems and for laser and photonics R&D for applications in energy, information technology, environment, medicine and health, transport and civil engineering, industrial minerals, and materials beneficiation. While maintaining a world-class R&D program, this center will implement a graduate program on education and training in nanoscience and nanotechnology. Moreover, attention will be paid to technology transfer into market products for socioeconomic growth.

Second, a workshop organized jointly by the United Nations International Centre for Science & Technology and the United Nations Industrial Development Organization (ICS-UNIDO) and NANOAFNET was held at iThemba LABS, Western Cape, South Africa on August 20–22, 2008, focusing on how nanoscience and nanotechnology should benefit the African continent. Subsequent to the productive inputs of various participating decision policy makers from Europe, China, Japan, USA, and Africa, it was concluded that competitive nanoscience/-technology solutions could be attained for two major challenging continental issues: nanotechnology for energy and water purification for rural areas specifically. The South African minister of the Department of Science & Technology, who delivered a comprehensive and visionary keynote address, confirmed the readiness of South Africa to support the outcomes of this workshop. He stated: ‘‘We therefore welcome this discussion and trust it will help to better networking and collaboration on nanotechnology. South Africa is prepared to support the ICS-UNIDO initiative on regional networking and to take on any tasks that come her way to ensure the success of this initiative’’. During the deliberation phase of the third day of the workshop, a virtual African Nanocenter was created officially with its headquarters located at iThemba LABS in Cape Town, South Africa. The NANOAFNET chairman Dr. M. Maaza has been mandated to follow up the implementation phase with the different stakeholders.

This is exciting news for the development of science and technology in Africa and should also be a source of inspiration for initiatives in other developing countries.

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