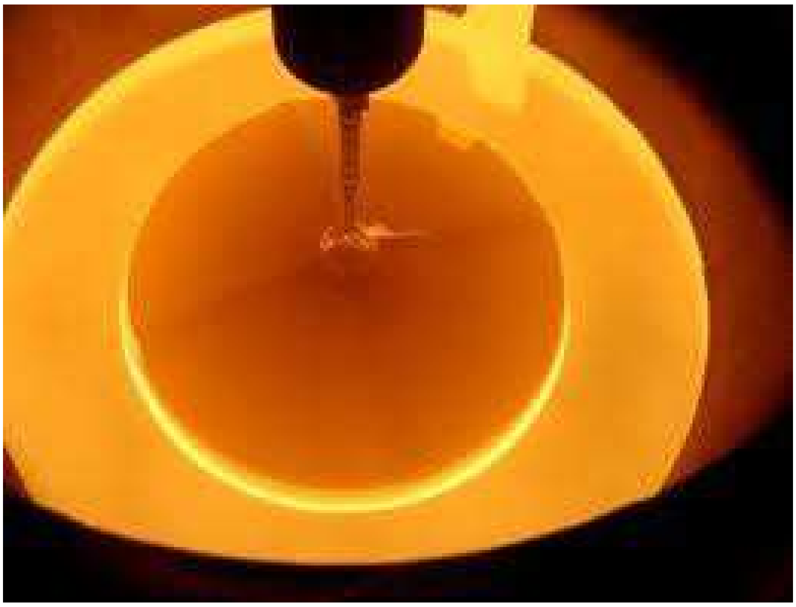
THE TECHNOLOGY OF SINGLE CRYSTALS AND EPITAXIAL LAYERS

THE CASE FOR ENERGY, WATER, HEALTH, EDUCATION AND SECURITY



A WHITE PAPER

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Contents:

Executive Summary

Crystal and Materials Technology (CMT) for Energy Savings, Renewable Energy, Health and Education

One of the chief issues facing the world today is energy (saving, transport, storage, and production) and its impact on the climate problem. Reliable electrical power, the supply of clean water (including water for irrigation) and the advancing lifestyle of billions of people hinge on the generation of cheap, abundant electricity. The major proportion of electrical power production today comes from fossil fuel-fired power plants. Their impact on the environment, both in terms of CO_2 emissions, contaminants and particle pollutants in the atmosphere, is widely expected to become catastrophic. As third world economies rapidly transition to first world consumption patterns, this problem is progressively increasing. (China and India together have over 800 new coal-fired power plants in the planning stage which actually represents a slow-down in the rate of Chinese power expansion after the large buildup of the last decade [Carrington, 2012]).

The primary limitation to the technological advances in improved electricity generation techniques and efficiencies is related to crystal and material technology just as the progress in computers, micro-electronics and communications was only possible due to crystal and material developments.

Advances in crystal and material technology needed for generation, transmission and storage of electricity will bring about the next big leap in technologies that result in greater availability of electric power to the entire human race. Failure to make these advances will result in severe damage to the environment and in growing damages caused by the increased frequency and intensity of hurricanes and other extreme weather conditions such as floods, tornadoes, blizzards and droughts and in the catastrophic effects of raising sea level. The following list details areas where advances in crystal and material technology will impact electricity generation, saving, and distribution and reduce CO_2 production.

1. Renewable energy
    a. Silicon photovoltaics (PV) improvements
    b. Gallium arsenide (GaAs) based concentrated photovoltaic (CPV) improvements
2. Energy savings:
    a. Illumination using high-brightness light-emitting diodes (LEDs)
    b. High voltage direct current (HVDC) power transmission
    c. High power rectifiers and inverters
    d. High Tc superconducting (HTS) cables
    e. HTS generators, transformers, motors, and current limiters
    f. HTS Magneto-hydrodynamic (MHD) ship propulsion
3. Energy storage
    a. Batteries
    b. HTS flywheels
    c. Superconducting Magnetic Energy Storage (SMES)
4. Health and Education
    a. Medical instrumentation (CAT, PET and ultrasound scanners, X-rays, laser diagnostics and surgery)
    b. Water disinfection by ultraviolet LEDs
    c. Large-scale irrigation for farming
    d. TV, PC and internet access for remote village education

5. Future nuclear fusion power generation
    a. First and second wall for magnetic confinement (TOKAMAK)
    b. Laser and non-linear optical (NLO) crystals for inertial confinement fusion (ICF)
    c. Diode arrays for laser pumping for ICF

Topic 2a alone will save 428 coal-fired power plants* corresponding to an annual reduction of 1.5 billion tons of CO_2*, whereas topics 2b to 2f and topic 3 will save many more coal-fired power plants. Topic 5 could give a nearly unlimited supply of electricity with relatively little radioactive waste.

To achieve the necessary breakthroughs in technology, emphasis must be placed on the education and training of crystal and material technologists. This white paper outlines the specifics of why this is important and how this can be achieved.

*The figure of 428 coal-fired power plants is derived as follows: the top 50 countries in CO_2 emissions from power production release a total of 10.6 trillion tons of CO_2 annually according to Carbon Monitoring for Action [Science Daily, 2007]. Germany, which releases 356 million tons, could abate 50 million tons by switching from incandescent to LED lighting [McKinsey, 2010]. Extrapolating to the top 50 countries and using the U.S. average of 3.5 million tons of CO_2 per year from a typical coal-fired power plant [UCS 2012] yields the 428 power plants.

1. Introduction / Background

This white paper is the creation of a group of scientists concerned with the future direction of educating and training chemical and materials engineers who will specialize in the field of crystal and material technology (CMT). CMT involves the industrial production of crystals and wafers/substrates; production of oriented epitaxial layers (epilayers) and multilayers onto the wafers; and the characterization of crystals and epilayers. CMT includes machines and furnaces for crystal and epilayer production, chemical precursors, equipment for crystal sawing and polishing, infrastructure, instrumentation for characterization, and all processes and equipment developments supported by theoretical and computer simulation efforts.

Synthetic crystal and epilayer production enabled the foundation of the modern electronics revolution and underpins all aspects of global commerce, communication, energy production and medical technology. It is key to the advances in electricity production and storage that will be critical to improving renewable energy technologies, energy storage and reduced energy consumption that are essential to reduce the impact of energy on global climate change.

The authors (experienced technologists in this field) convened a meeting of specialized colleagues from Europe, Asia and the United States for a week in Poulithra, Arcadia, Greece in May 2012 to discuss the need for the requisite education and training of future engineers and scientists who will form the first generation of crystal technologists with basic knowledge of all above-mentioned topics of CMT enabling the CMT engineers to significantly accelerate progress and to consult for specific problems and collaborate with leading specialists of the individual fields.

2. Abstract

Since man's first appearance on this planet, his technology has been limited by his mastery of the materials available for making tools. Thus the ages of man are defined by the primary materials used at the time – Stone Age, Bronze Age, Iron Age, etc. One could argue that the current age, which began with the invention of the transistor in 1947, should be called the Silicon Age because so much of our modern technology is based on integrated circuits (the so-called "microchip") made from crystals of high purity silicon. In fact, a large array of materials is required to keep the tools of our modern civilization functioning. In virtually every case, they must first be grown as a large perfect crystal of very precise purity specifica-

tions. A great deal of crystal technology requires the epitaxial deposition or “growth” of multiple single crystal layers (epilayers) on a substrate or wafer after this had been machined from large single crystals. Most microelectronic circuits in use today include epitaxy at one or more stages of the manufacturing process, particularly for high-end electronics.

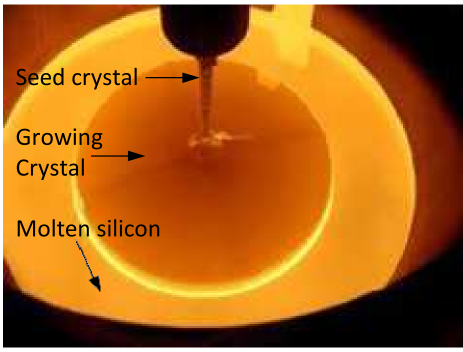
The key advances in crystal technology have been made in the university, government and industrial laboratories. The golden age of new materials’ discoveries occurred in the two decades beginning around the mid-1960s. This period saw the discovery and development of such materials as gallium arsenide, yttrium aluminum garnet, synthetic quartz, cadmium telluride, indium antimonide and lithium niobate, among others. Table 1 is a list of many of the materials discovered and commercialized in the last 50 years. This table is by no means comprehensive.

The generation of scientists and engineers that spearheaded this development is now retiring from the industrial, academic and national laboratories. Without new scientists and engineers trained in the field of crystal and material technology, mankind risks slow progress in crystal and material’s based developments relevant for energy and for novel technologies. Furthermore, the new generation of crystal technologists must strive to apply the single optimum technology (for a given crystal or epilayer for a specific application) whereas so far non-optimized processes are often applied using unnecessarily large resources.

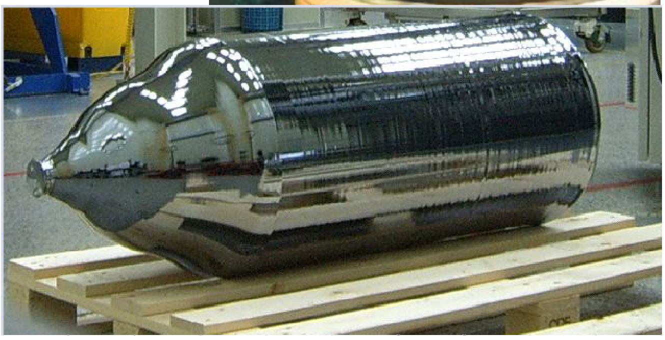
Table 1

Crystalline Material	First Developed	Applications
Ruby*	1890s	Watch bearings, synthetic gemstones
Germanium	1940s	Transistors
Quartz	1950s	Oscillator crystals (radios, watches, etc.)
Sapphire*	1950s	Windows, substrates, wear surfaces
Silicon	1950s	Transistors and integrated circuits
Alkali halides (NaI)	1960s	Scintillation Detectors
Cadmium Telluride	1960s	Infrared Sensors
Gallium Arsenide	1960s	Microwave electronics, LEDs, etc.
Indium Antimonide	1960s	Infrared Sensors
Lithium Niobate	1960s	Surface Acoustic Wave (SAW) devices
Ruby*	1960s	Lasers
Yttrium Aluminum Garnet (YAG)	1960s	Lasers
Yttrium Iron Garnet (YIG)	1960s	Microwave resonator
Alexandrite	1970s	Lasers
Gallium Phosphide	1970s	Red LEDs
Indium Phosphide	1970s	LEDs
Lithium Tantalate	1970s	Microwave oscillators
Silicon Carbide	1970s	High temperature semiconductors
Lutetium orthosilicate	1980s	Scintillation Detectors
Yttrium vanadate	1980s	Lasers, repeaters in fiber-optic internet connections
Titanium-doped Sapphire	1980s	Lasers
Gallium Nitride	1990s	Blue and White LEDs

***Sapphire and ruby are aluminum oxide and are chemically identical except ruby has chromium impurities which impart the red color. A ruby crystal was used for the first laser in 1960.**



Clockwise from above: a silicon crystal in the early stages of being "pulled" from the high-melting liquid using a thin seed crystal; in the process of removal from the growth chamber; on a pallet prior to being processed into wafers.



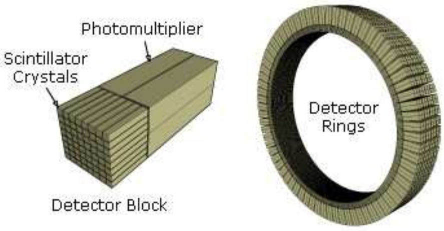
3. Application Examples

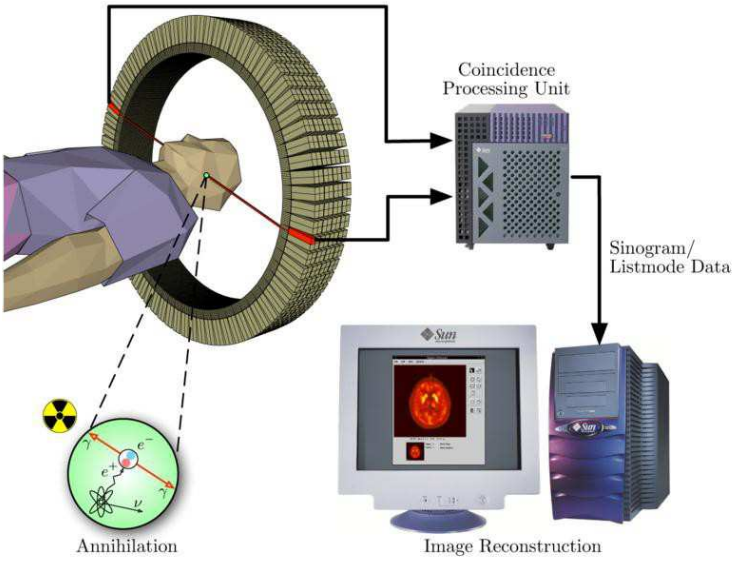
Everything in our modern advanced technology culture – from radios to radiation therapy, from cell phones to solar cells, from ATMs to GPS, from laser pointers to laser printers, from airport security scanners to aircraft engines – depends on synthetically-grown, single crystals. The internet, which supports our knowledge-based economy, would not exist without them. The following pages show just a sampling of modern technological advances for which single crystals and epilayers of various materials are fundamental.

LED bulbs for general lighting applications. Left: A 40 watt bulb made from four high-brightness LEDs of GaN epilayers on a sapphire substrate. Right: 65 watt equivalent bulbs made with GaN epilayers on silicon carbide (SiC) substrates which consume only 9.5 watts of electrical power.

Medical

Lutetium Orthosilicate
Scintillator Crystals



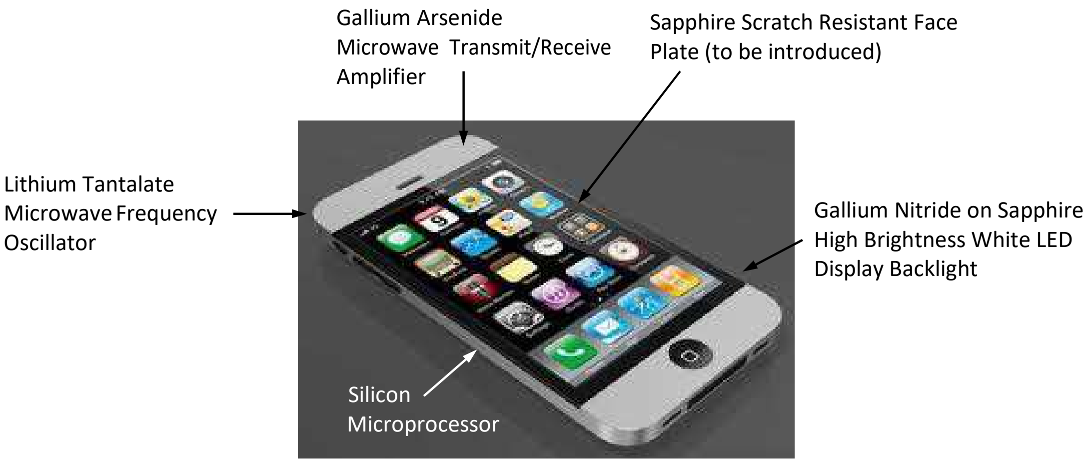


Virtually every aspect of modern medicine is dependent upon a variety of devices and instrumentation based on single crystals and solid-state electronics. Single crystal lasers such as neodymium-doped, yttrium aluminum garnet (Nd:YAG) and chromium-doped chrysoberyl (alexandrite) are used for surgery both for simple procedures such as mole and tattoo removal and more complex operations such as laser ophthalmology and laser scalpels. Sapphire, the second hardest material in nature after diamond, is also used for surgical scalpels. PET scanners (pictured) rely on a large ring array of scintillator crystals (lutetium orthosilicate) and advanced computer hardware to create a non-invasive image of internal body organs. Digital x-rays using CCDs (charge-coupled devices) similar to those in a digital camera have replaced x-ray film in dentists' offices. Ultrasound produced from oscillator crystals are used for standard diagnostics

Consumer Electronics

Crystals appear in the components of virtually all of the common consumer electronics such as cell phones, MP3 players, calculators, radios, TVs, remote controls, personal computers, kitchen appliances, hearing aids, tablet computers, etc. Electronics based on improved crystals and epilayers will reduce power consumption.

Telecommunications



Note: The iPhone is shown only as an example of a typical cell phone. Different phones may use other components.

Solid-state electronics based on crystals and epilayers is the backbone of the worldwide telecommunications and internet systems. Cell towers, computer phone routing, communications satellites, fiber optics, internet repeater nodes, server farms right down to the handheld mobile phone—every component of the telecommunications and internet networks is crucially dependent on a variety of crystals. Communication speeds, data handling rates, security and encryption all rely on the latest technological advances in crystal and materials technology. The key question is, “What crystals and materials will be required for the next generation of these technologies and where will they come from?”

Automotive

Automobiles clearly demonstrate the reliance of our contemporary lifestyle on crystal-based solid-state electronics and sensors. GaN LED headlights have increased lifetime, and GaAs-based electronics have improved temperature resistance and radiation hardness. Soon, traffic and speed control, toll collection and localization of individual cars will be possible.

Business Electronics

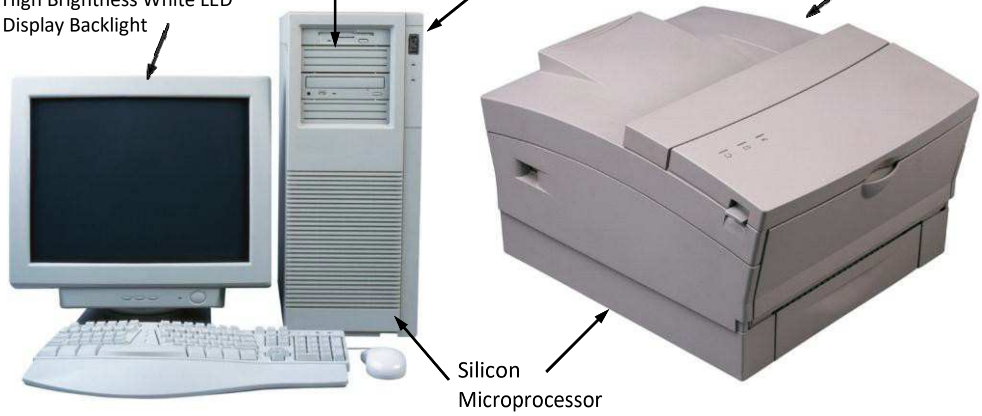
In addition to the common PC and printer, crystal technology is an important component of faxes, copiers, routers, servers, network storage, etc.

Gallium Nitride on Sapphire
High Brightness White LED
Display Backlight

Gallium Arsenide
Diode Laser for CD/DVD
Reading and Burning

Quartz
Oscillator for Clock and
Processor Timer

Gallium Arsenide
Diode Laser for
Laser Printer



Silicon
Microprocessor

Military / Defense

Sapphire
Transparent Armor

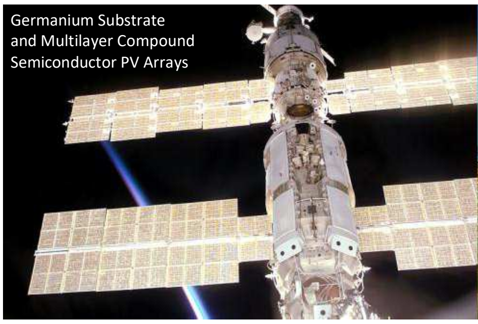
Neodymium doped Yttrium Aluminum Garnet
Laser Target Designators and
Range Finders

Cadmium Telluride
Infrared Sensors

Sapphire
Scratch Resistant Windows
and Domes for Infrared
Optics

Neodymium doped Yttrium Aluminum Garnet
Laser Target Designators and
Range Finders

4. Energy Solutions



Potential of GaN for Saving Energy

A recent development is the high bandgap semiconductor gallium nitride (GaN) grown as an epitaxial layer on sapphire wafers by Akasaki and co-workers (1989). LEDs of this material emit blue light making possible full-color, high brightness outdoor displays such as the one at the NASDAQ trading exchange shown in the photo. Gallium nitride was then developed as a commercial material by Nakamura et al. (1994) at the Nichia Corporation in Japan.

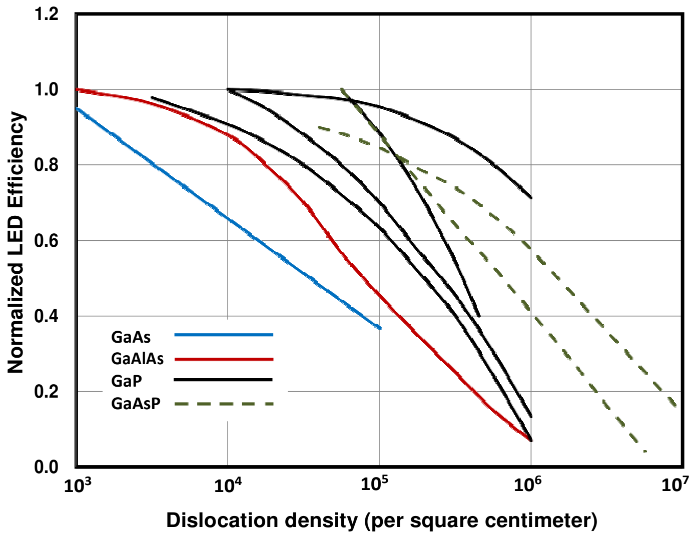
Due to its short wavelength emission, GaN can be color shifted mainly by means of phosphors to longer wavelengths allowing it to produce virtually any color light including, most importantly, white light. This makes it the material of choice for back-lighting of flat screen TVs and computer displays as well as high efficiency light bulbs for general lighting applications. A satellite view of the earth at night shows the vast amounts of energy used for lighting both interior and exterior. The continued development of LEDs to higher light output (in terms of lumens/watt) offers the potential to save huge amounts of power. For example, the figure on page 10 shows the efficiency improvements realized in GaAs LEDs as a function of improved crystal quality (here shown as lower dislocation density); redrawn from Lester et al. 1995.

Similar improvements in efficiency and light output can be expected in GaN LEDs for white light production provided that comparable advances in crystal growth technology are achieved. It is reasonable to project light output improvement to 200 lumens/watt from the current 100 l/w with greater crystalline quality. Other energy-saving applications of GaN- and SiC-based devices include high-power, high-temperature transistors and rectifiers/inverters for DC power transmission and for electro-technology

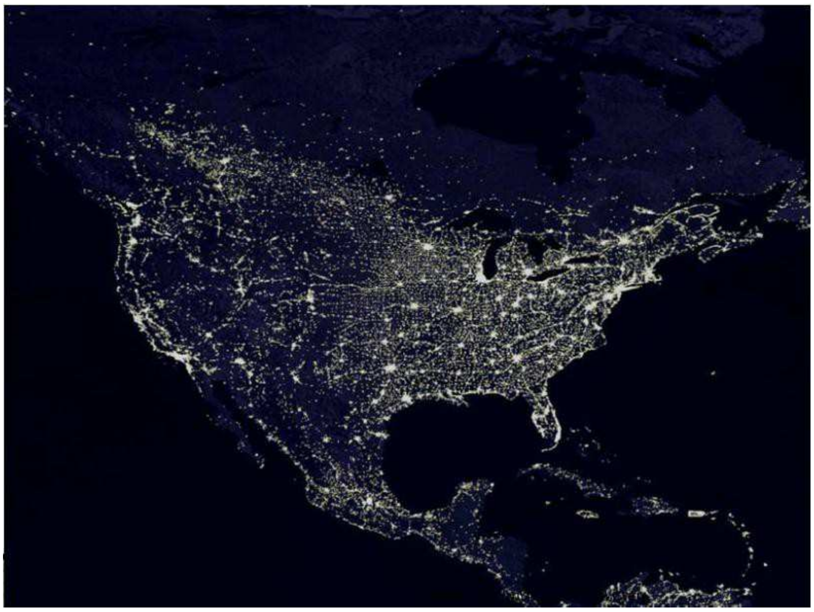
Saving in Electric Power Transmission

Considerable energy savings can be realized by careful attention to the design of electric transmission grids (SMART). Traditionally, electrical energy is transmitted as high-voltage AC, 3-phase power using three above-ground wires from the power generation site (fossil fuel-fired power plant, hydroelectric dam or nuclear reactor) to substations for reduction to lower voltage distribution lines to the end user. The AC loss is about 15% per 1,000 km [IEA / OECD 2012].

An alternative method of power transmission consists of a single high voltage, DC line (HVDC) to the substation with only 3% loss followed by inversion to AC simultaneous to stepping the voltage down to levels for end user application. This has the advantage that less metal is used for the single wire—the earth acts as the "return" wire—and it allows the placement of the single line underground making it immune to interruptions caused by storm damage or terrorist attacks. For the design and construction of economic high-power inverter components to convert the DC back to AC, the crystal and materials technology is the key issue. Such systems already exist in North America, China, South Africa and Brazil.



Extension of grids continues around the world and roughly tripled between 1970 and 2009 (primarily in China which accounted for 60% of the world-wide addition) [IEA / OECD 2011a]. Since photovoltaics inherently generate DC power, it is logical to transmit the power as DC rather than invert it to AC. An example is DESERTEC (www.desertec.org) which is proposing to place photovoltaic generators in sunny areas of the Mediterranean region and distribute the power via HVDC to more industrialized areas in Europe where weather conditions limit the efficacy of photovoltaics



This satellite view of North America at night illustrates the enormous amount of energy used for lighting for both interior and exterior purposes.

Renewable Energy: Photovoltaics

Most of our energy was delivered from the sun, be it in the form of fossil fuels (coal, oil or gas) which nowadays are our primary energy sources. Other forms of solar energy are based on climate: precipitation for hydro-energy, wind, sea waves—and on related warming of the ground and of the sea. Nuclear and geothermal energy are exceptions and not dependent on the sun. With the development of the semiconductor crystal materials the direct absorption of sun light and transformation to electricity has been achieved (photovoltaics or PV).

Driven by large subsidies from governments, industries producing solar panels from silicon have been developed. However, the most economic fabrication of Si thin-film panels yield the lowest efficiency and lifetime, and the efficiency is increasing to slightly above 20% with increasing crystal perfection requiring improved fabrication technologies, most of which are not optimum. Problems with PV-silicon are its limited efficiency and thermal stability, the temporal and storage limitations, and the amount of energy required for its production, so that return of investment can only be received from government subsidies providing high feed-in tariffs for electricity delivered to the public grid.

Recently developed multilayer compound semiconductor solar cells absorb a larger fraction of the solar spectrum and can withstand higher temperatures. Their efficiencies are potentially at least twice that of conventional silicon solar cells [IEA / OECD 2012]. Their drawback is that, to make them practical, they must be combined with a concentrator (lens or reflector) with sun tracking which requires that they be used in areas of nearly constant sunlight (deserts) rather than more temperate regions which experience frequent cloud cover. Another advantage is that the required land area is significantly lower than with PV-Si. Advances in crystal and materials technology and processing are key to making these concentrator photovoltaics (CPV) practical. Combining such a solar array with the HVDC transmission lines described above could make a significant contribution to a sustainable and renewable energy scheme.

The Potential of High-Tc Superconductors

Another energy saving technology in power transmission is the use of high-temperature superconducting (HTS) materials for the transmission lines. Here the materials challenges are significant as HTS materials are still in the early developmental stages. Although the principle has been demonstrated and the basic materials have been identified, much serious crystal and materials research remains to be done before a practical HTS system can be implemented. “Unfortunately, the complex chemical and structural nature of the HTS compounds and their limited thermodynamic stability were not appropriately considered in the physics-dominated research, even reproducibility of solid-state physical experiments was in general not achieved in the hectic ten [now more than 25] years following the promising HTS discovery so that the development of HTS theory was also hampered” [Scheel, 2008]. Here again, the development by well-educated crystal and materials technologists is the limiting factor to the full exploitation of the potential of HTS compounds.

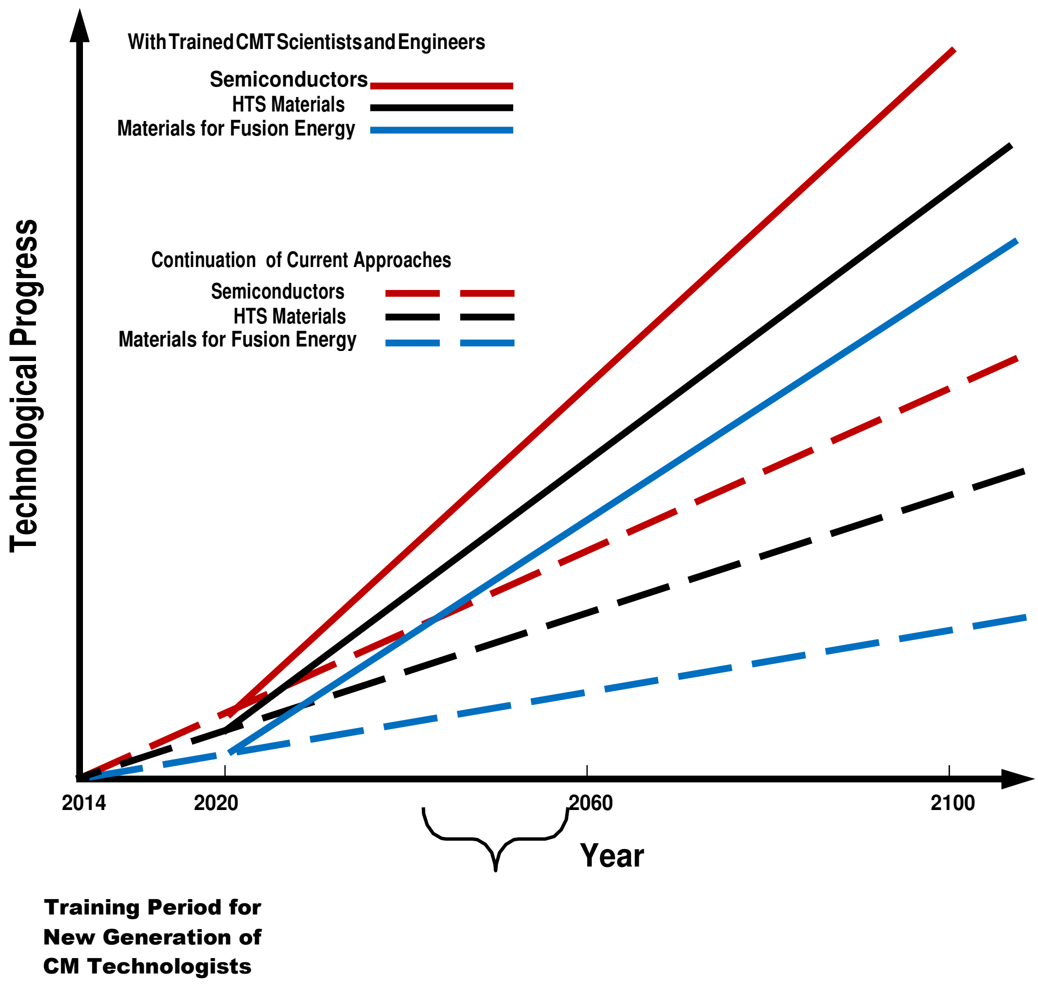
5. The Problem: Lack of Education of Crystal Technologists

Worldwide, the education of crystal technologists has not been established. Significant resources were spent for unsatisfactory developments in promising high-temperature superconductivity applications due to defective non-optimized crystal and epitaxial materials and processes. The development of computers, communication technology and modern electronics has taken more than 50 years because well-educated crystal technologists did not exist. Early education of crystal technologists could have achieved the development of the crystal base for the modern electronics age within perhaps only 20 years at comparably smaller budgets.

Although the role of crystal technology in medicine (for example CT scanners, artificial joints, heart pacemakers, etc.), in communication and security is clearly established, there still is no formal educational opportunity for crystal technologists. Now, with the expected challenges of climate change and the related energy problems, the education of crystal technologists and energy-specific materials engineers should get the highest priority, especially in view of media-enhanced doubts about nuclear energy and the policy of "Energiewende*" in Germany and Switzerland [MacKay 2009].

Energy (followed closely by water) has become the world's number one problem (see Appendix 2). Examples of the impact of crystal technology on energy savings, energy transport, renewable energy technologies, energy storage and on the future hopes of practical fusion energy and high-temperature superconductivity, with its great potential for the energy problem, are shown in Appendix 3.

* *Energiewende* is the public policy of transitioning away from nuclear power towards more renewable sources such as photovoltaics, wind, biomass, geothermal, etc. This dream of politicians and of the "green" fraction of the population can only be realized after educated crystal and material technologists have established the technical prerequisites. Perhaps, one should in a first phase continue the relatively safe nuclear energy by continuing the development of very safe reactors of the third and fourth generation and a safe radioactive waste disposal technology. In this phase, the coal- and oil-fired power stations should be reduced due to their significant risks of life and health and due to their catastrophic impact on the climate.



The authors expect reinforced developments after scientists and engineers have been educated in Crystal and Material Technology (CMT) and have learned to develop optimized technologies for economic fabrication of crystals, layers and materials for the highest performance devices.

Semiconductors: PV – Si and CPV – GaAs-based photovoltaics, AC-DC and DC-AC converters, LEDs for illumination, high-power transistors, etc.

HTS: High-Temperature Superconductors for many energy-relevant applications.

6. The Proposed Solution

The problem facing the education of crystal technologists is that it is multidisciplinary. Crystal technology should be treated as its own scientific discipline which does not fit into a single classical department of universities and engineering schools. It requires an educational foundation in a wide variety of disciplines including:

- Materials Science and Engineering including:
  - Phase diagrams & Phase transformations (solidification, sublimation, etc.)
  - Thermodynamics
  - Metallurgy, Ceramics, Glasses
  - Crystal growth (including epitaxial layers)
- Inorganic Chemistry (especially high temperature chemistry)
  - Chemical Engineering
  - Analytical and Organic Chemistry
- Mechanics including:
  - Hydrodynamics and Aerodynamics
  - Vacuum technology
  - Machine design & Process Control
- Applied Crystallography & General Characterization
- Solid-State Physics and Surface Physics
- Statistical Mechanics & Computer Simulation
- Electrical Engineering
- Mathematics & Informatics

A proposed curriculum for crystal technology education for both an undergraduate and master's degree course is referenced in Appendix 5.

Roadmap to a Solution / Recommended Actions

No university or engineering school, even those focused specifically on the technical fields, has a degree program tailored to the specialize discipline of crystal technology. One solution to this problem would be to endow chairs at one or more institutions specifically to train individuals in this field and to give courses complementary to the other courses in sciences, technology and management. Companies with specific requirements for advanced materials in crystalline form could be encouraged to fund such an endowment and at the same time should request crystal and material technologists and offer summer jobs for the students. These companies would include the following industries:

- Crystal and Epilayer Production
- Energy
- Electronics / Computers
- Lasers and Electro-Optics
- Medical Instrumentation
- Crystal Machining (Sawing, Lapping and Polishing Machines)
- Machines / Furnaces for crystal and epilayer production and for wafering (saws, polishing machines etc.)
- Military/Defense

Sematech (consortium of 14 US electronic companies), SEMI Europe, CristalINNOV France and other organizations should take initiatives for establishing education of crystal and material technologists. Fund-ing Agencies & National Science Foundations should dedicate a certain percentage of funds (5 to 10%) of large research facilities (ITER, CERN, PSI etc.) for CMT education and development in order to accelerate progress in research with improved crystal and material samples.

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Appendix 1

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Frank J. Bruni: Dr. Bruni was born in the United States and received his baccalaureate degree with honors from the University of Pennsylvania and his doctorate from the University of Oxford (both in metallurgy). He has worked for over 40 years in high temperature oxide crystal growth. Dr. Bruni was employed at Oak Ridge National Laboratory, Texas Instruments and Allied Chemical before founding Material Progress Corp. in Santa Rosa, California. MPC is now owned by II-VI, Inc. Dr. Bruni continues to reside in Santa Rosa and has worked as a consultant in the field of crystal growth since 1985. His list of clients and publications can be found on his website (www.FrankBruni.com). He has two children from his first marriage and two grandchildren. He is currently married to Ms. Frances Cordova. His hobbies include art (watercolors and etchings) and writing. He has contributed a regular monthly column on puzzles and technical articles to the local Mensa chapter's newsletter for over 13 years.

Hans J. Scheel, born 1937, Swiss citizen, chemical background, has worked 25 years in universities in Switzerland, Brazil (as full professor) and Italy and 21 years in chemical, electronic and machine industries in Germany, Switzerland and USA. After retirement from Swiss Federal Institute of Technology (ETH) he was visiting professor/invited scholar at Osaka and Tohoku Universities, Japan and at Shandong University, China. Besides crystal growth of numerous materials for research, he has experiences in synthetic and analytical chemistry, organic pigment dyes, glass ceramics, crystal growth and epitaxy of high-Tc superconductors, liquid-phase epitaxy of GaAs and of GaN, and in design of crystal growth machines and an ultra-glovebox. He was co-organizer of European and International conferences and schools and organized four International Workshops on Crystal Technology between 1998 and 2008. He was a member of committees and session chairman of numerous conferences and has given more than 150 international invited lectures. Hans Scheel is the author of 120+ technical publications and patents and co-author and editor of seven books in the field. For his inventions and achievements he received the Dr. of Engineering from Tohoku University Japan, was elected member of the Russian Academy of Engineering Sciences, and got awards from Swiss, British and Korean Crystal Growth Associations and from IBM. After retirement he started the company Scheel Consulting and got involved, in addition to education of crystal technologists for energy, in a high-safety airliner concept and in Tsunami protection barriers. Besides former and present memberships in American, British, German, Japanese and Swiss Crystal Growth Associations he recently became member of Tsunami Society International.
From his first marriage Hans has two sons and two grown-up grandchildren. Now he is married to Regula Hauser Scheel, born Ziegler. His hobbies are classical music and history of crystal technology. hans.scheel@bluewin.ch www.hans-scheel.ch

Appendix 2

According to Richard Smalley, Nobel Prize Chemistry, 1996 [Smalley, 2003]

Humanity's Top Ten Problems for next 50 years

- **ENERGY**
- WATER
- FOOD
- ENVIRONMENT
- POVERTY
- TERRORISM & WAR
- DISEASE
- EDUCATION
- POPULATION
- DEMOCRACY

2004	**6.5**	**Billion People**
2050	**~ 10**	**Billion People**

Appendix 3

The Importance of Crystal and Material Technology for:

Energy Generation and Savings

- Illumination by economic (Ga, Al, In)N LEDs of higher efficiency (>150 lm/W, compared to present LEDs with 60 to 100 lumens/W)
- Improved High-Temperature High-Power Transistors (SiC, GaN)
- Improved DC/AC and AC/DC Converters for DC Current Transport
- High-Temperature Superconductivity (HTS)
  - HTS Transport of Electricity
  - HTS Transformers
  - HTS Generators
  - HTS Current Limiters
  - HTS for MHD (magneto-hydrodynamic propulsion) of ships
  - HTS for Levitating Trains, etc.

Renewable Energy

- Photovoltaic Silicon Solar Cells (higher efficiency >18%, economic)
- Concentrated Photovoltaic Solar Cells (highest efficiency >35%, economic)
- Thermoelectric Photovoltaic Cells

Energy Storage

- New Battery Systems
- HTS Energy Storage (Flywheel, SMES Superconducting Magnetic Energy Storage)

Future of Nuclear Fusion Energy

- Large Radiation-hard High-Power LASER Crystals
- Large Radiation-hard NLO Crystals for achieving UV Radiation
- Economic LASER-Diode Arrays for Pumping the LASER Crystals
- First-wall material for Tokomak (magnetic confinement) Technology

Appendix 4

Impact on Five of Smalley's Top Ten Problems of Humanity

CPV DC electricity and solar warm water from sun-exposed roof installations for

- long-life storage battery
- air conditioning, refrigeration and washing
- LED lighting
- Blue/UV LEDs for water disinfection
- TV & Internet from satellite / DC equipment for education and communication
- DC motors, pumps, saws with transportable storage batteries

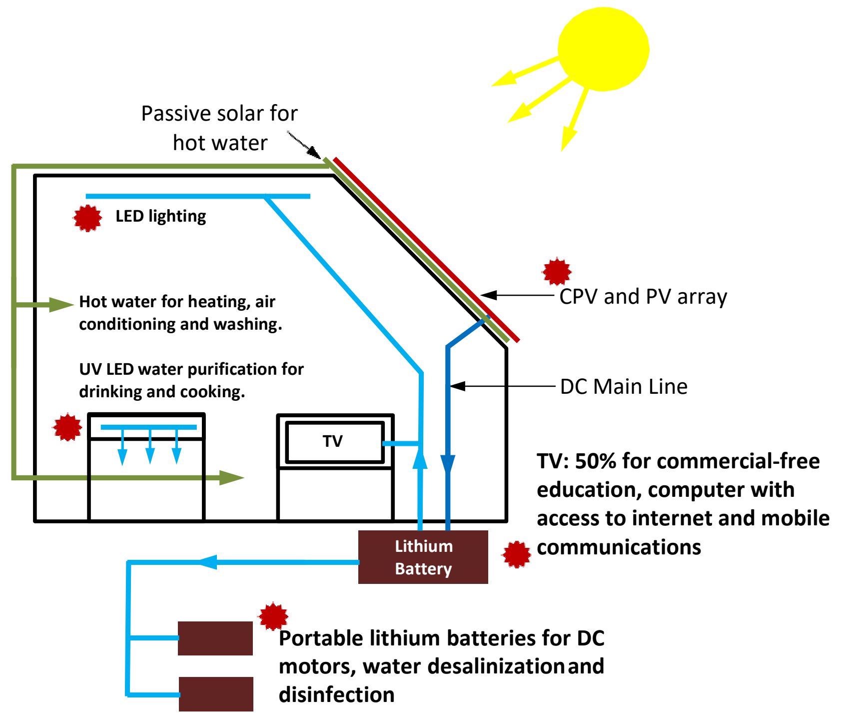
Large-scale irrigation for

- agriculture and food production
- biomass production for fuel (example ethanol from sugar cane in Brazil) for emergency power supply for bad-weather period
- forest development for climate and for heating / cooling without electricity

Energy is a main cost factor

- for desalination of water
- pumping water to arid areas
- fabrication and transport of pumps, piping and machines for farming
- transport of soil, seeds, fertilizer

Worldwide approximately 1.3 billion people are without electricity in Africa, Asia, South America and in the Southern European countries, and 2.7 billion still rely on traditional biomass (wood, etc.) for cooking (IEA / OECD, 2011b) .



Requires education of crystal and materials technologists

Example of areas where CMT impacts quality of life issues in third world nations without a rural electricity grid.

Appendix 5

Recommended Education & Training in Crystal Technology:

A. Undergraduate Level

The undergraduate courses should provide the crystal technologist with the multi-disciplinary skills to communicate with specialists (chemists for delivering chemicals, crucibles and gases), thermodynamicists, theoretical physicists, simulation experts, machine and furnace designers, device engineers, characterization experts.

- **Chemistry:**
    - General Chemistry
    - Inorganic Chemistry and Organic Chemistry
    - Physical Chemistry
    - Analytical Chemistry
    - Thermodynamics & Thermochemistry
- **Chemical Engineering** with emphasis on
    - Mass Crystallization, Recrystallization & Zone Melting for Purification
- **Materials Science & Engineering:**
    - Metallurgy
    - Ceramics/Glasses
    - Polymers/Composites
    - Phase Diagrams / Thermal Analysis
    - Transport Phenomena (Mass Transfer, Heat Transfer)
    - Basic Crystal Growth
    - Dendrites; Casting
- **Crystallography:**
    - Symmetry, Space Groups, Miller Indices/Lattice Constants
    - Applied Crystallography
      (Texture, Powder Identification, Crystal Orientation)
    - Crystal Chemistry & Mineralogy/Geochemistry
    - Crystal Structure – Growth Habit
    - Crystal Defects
    - Structural Characterization (Diffraction Methods using X-Rays, Electrons, Neutrons, Gamma Rays and other methods)
- **Mathematics & Informatics** including:
    - Basic Computer Simulation,
    - Statistics
- **Physics:**
    - Solid State Physics (Semiconductors, Superconductors, Laser, Nonlinear Optics, Defects)
    - Statistical Mechanics
    - Surface Physics including STM, AFM
- **Electrical Engineering:**
    - General Circuit Mathematics
    - Microelectronics,
    - Electronic and Optoelectronic Devices,
    - Radiation Detectors
- **Mechanical Engineering** including
    - Hydrodynamics (Experiments & Simulation) & Aerodynamics
    - Machine Design,
    - Process Control
- **Energy and Climate problem: Role of Crystal and Material Technology**
- **Ecology/Environment**
- **Examination** (Bachelor in Engineering; as a prerequisite for a Master's Degree program)

B. Curriculum for a Master's Degree in Crystal and Material Technology (CMT)*

- **Fundamentals of Crystal Growth:**
  - Nucleation/Supersaturation
  - Growth Mechanisms
  - Growth Habit
  - Growth from
    - Aqueous Solution with Experiment,
    - Sublimation and Chemical Vapour Transport with Experiment
    - Recrystallization for Purification with Experiment
    - Growth from Melts with Experiment, Verneuil
    - Zone Melting (Pfann)
- **Fundamentals of Epitaxy:**
  - Hetero- and Homo-epitaxy
  - Growth Modes and their Control by Supersaturation and Substrate Properties
  - Substrates
    - Substrate Issues: Lattice Misfit, Misorientation, Dislocation Density, Thermal Expansion Differences with Epilayer, Surface Quality
  - Surfactants
  - Surface Reconstruction
  - Interfaces
  - Multilayers, Superlattices, Nanostructures
- **High Temperature Technology:**
  - Heating Methods (resistive, radiative, induction, microwave)
  - Furnace and Hot Zone Design
  - Heating Elements, Insulation Materials
  - Crucibles
  - Reactivities / Corrosion / Ellingham Diagrams
  - Thermal and & Vibration Insulation
  - Temperature Measurements
- **Vacuum Technology:**
  - Pumping Systems
  - Vacuum Vessels & Lines
  - Outgassing & Permeability
  - Vacuum Measurement
  - Partial Pressure Adjustment
  - Measurement of Trace Gases
  - Vapour Pressures
  - Mass Spectrometry
- **High Pressure Technology:**
  - Compressors and Autoclave Design; Safety Valves
  - Pressure Systems and Monitoring
- **Crystal Growth Methods (Specific Examples with Details):**
  - From Solution (Slow Cooling / ACRT, Circulation / Stirrer)
  - Top Seeded Solution Growth
  - Hydrothermal
  - Growth from Melts
    - Verneuil
    - Tammann-Stöber/VGF/HEM
    - Bridgman-Stockbarger/ACRT
    - Czochralski (Little/Teal) / LEC
    - Skull Melting
    - Float Zone and Zone Melting
  - Vapour Growth (Piper Polich, Chemical Transport/Schäfer).

- **Growth Experiments:**
  - Growth of Inclusion-Free Crystals (Ivantsov Diffusional Undercooling / Constitutional Supercooling of TJRCh, Maximum Stable Growth Rate of Scheel & Elwell)
  - Growth of Dislocation-Free Crystals (Dash, Billig, Indenbom/Milvidskij, Jordan, Müller/Völkl)
  - Growth of Striation-Free Crystals (Scheel/Rytz/Swendsen)
  - Equipment & Resources
  - Experimental and Numerical Simulation
- **Casting:**
  - Dendritic Growth
  - Turbine Blades
- **Solid State Crystallization**
- **Epitaxy Methods:**
  - Liquid Phase Epitaxy (LPE)
  - Molecular Beam Epitaxy (MBE)
  - Organo-Metal Vapour Phase Epitaxy (OMVPE/MOCVD)
  - Atomic Layer Epitaxy (ALE)
  - Growth parameters to control the growth mode and perfection of epilayers
- **Single Optimum Growth Technology for a specific Crystal or Epilayer for a specific Application** based on all relevant parameters (thermodynamics, economy, ecology, infrastructure, timeliness, safety, etc.)
- **Examples of optimum growth** (Silicon by Czochralski & Float Zone) and of non-optimized growth (Silicon for solar cells)
- **Important Materials / Production in Industry / Applications of Crystals and Epilayers, Multilayers:** Si, Ge, GaAs, InP, GaP, CdZnTe, ZnO, Quartz, Al_2O_3, SiC, GaN, AlN, Nd:YAG & other LASER crystals, $LiNbO_3$, KDP, KDDP & other NLO borate crystals, Scintillation Crystals (halides, Lu-silicate), Optical Crys- tals, magneto-optic garnets, ZrO_2, Diamond; High-Tc Superconductors
- **Multilayers** of (Ga,In)(As,P), GaAlAs, CdHgTe (CMT), GaInAlN
- **Characterization of Crystals and Epilayers/Multilayers** by analytical, spectroscopic methods (ICP, mi- croprobe) and by diffraction (X-ray topography), optical (Polarizing Microscope, TEM) and electronic meth- ods, infrared tomography; etc.
- **Sufficient Characterization** for Reproducible Solid-State Physics
- **Surface Characterization** by Nomarski, Tolansky, STM, AFM, SEM, LEED, etc.
- **Crystal Machining:** Crystal Orientation, Sawing/Slicing, Lapping, Polishing, Wafering, Micromachining, etching, with practical work and defect/surface characterization; visits of industries
- **Design of Furnaces/Machines for Crystal Production, Epilayer Production, Crystal Machining**
- **Two weeks in Model shop:**
  - Metal working; Soldering; Welding
  - Glass & Quartz Glass Blowing
- **Two Each - Three Summer Months Internships in Industry:** Crystal Factory, Epilayer/Device Fabrica- tion, Crystal Machining, Machines for Crystal and Epilayer Production, Machines for Crystal Machining
- **Infrastructure:** Clean room; reliable electricity and water supply; control of temperature, humidity and vibra- tion
- **Work Safety, Insurance Aspects**
- **Management**
  - Work plan
  - Spread-sheet Analysis / Cost of Ownership
  - Business Plan
  - Intellectual Property Aspects
- **History of Crystal Growth, Crystal Technology & Materials Science**
- **Thesis**
- **Examination with Defense of Thesis**
-

GLOSSARY

Abbreviation	Meaning
AC	Alternating Current electricity
ACRT	Accelerated Crucible Rotation Technique - used for solution- and melt-grown crystals
AFM	Atomic Force Microscopy for surface characterization
ALE	Atomic Layer Epitaxy - used to grow thin layers and superlattices
AlN	Aluminum Nitride
Al_2O_3	Aluminum Oxide (sapphire), a very hard crystal used for windows, wear surfaces, substrates
CdHgTe	Cadmium MercuryTelluride
CdTe	Cadmium Telluride - a class of crystals used for infrared sensors
CdZnTe	Cadmium Zinc Telluride
CMT	Crystal and Material Technology
CPV	Concentrated Photovoltaics - high-efficiency solar cells with a lens or other optical concentration devices
Czochralski	Production of crystals by pulling from the melt (see cover photograph)
DC	Direct Current electricity
GaAlAs	Gallium Aluminum Arsenide - a compound semiconductor used for microelectronics
GaAs	Gallium Arsenide - a compound semiconductor used for microelectronics and LEDs
GaAsP	Gallium Arsenide Phosphide
GaInAlN	Gallium Indium Aluminum Nitride - a compound semiconductor used for LEDs and high frequency ICs
GaN	Gallium Nitride - a compound semiconductor used for blue and white LEDs
GaP	Gallium Phosphide - a compound semiconductor
HEM	Heat Exchanger Method - a crystal growth technique (variant of Bridgman)
HTS	High Temperature Superconductor - a material that becomes superconducting above 40Kelvin
HVDC	High Voltage Direct Current - an alternative high power electrical transmission method
IC	Integrated Circuit
ICF	Inertial Confinement Fusion - a nuclear fusion technology using LASER and nonlinear-optic (NLO) crystals
ICP	Inductively Coupled Plasma spectroscopy - a chemical characterization technique
InP	Indium Phosphide - a compound semiconductor used in microwave circuits
KDDP	Deuterated Potassium Di-Hydrogen Phosphate - a NLO crystal
KDP	Potassium Di-Hydrogen Phosphate - a NLO crystal
LEC	Liquid-encapsulated Czochralski - a crystal growth technique using an inert liquid layer above the melt
LED	Light Emitting Diode
LEED	Low-Energy Electron Diffraction - a characterization technique
$LiNbO_3$	Lithium Niobate - a piezoelectric crystal similar to quartz
$LiTaO_3$	Lithium Tantalate - a piezoelectric crystal similar to quartz
LPE	Growth of Perfect Layers and Surfaces by Epitaxy from the liquid phase
MBE	Molecular Beam Epitaxy - a method for growing thin epitaxial layers and superlattices
MHD	Magneto-Hydrodynamics
MOCVD	Metal-Organic Chemical Vapor Deposition - a method for growing epitaxial layers from metal-organic precursors
NLO	Non-Linear Optics - a class of crystalline materials used for frequency multiplication
OMVPE	Metal-Organic Vapor Phase Epitaxy - a method for growing epitaxial layers from metal-organic precursors
PV	Photovoltaics (solar cells)
SiC	Silicon Carbide - a compound semiconductor for high-temperature electronic applications and for LEDs
STM	Scanning Tunneling Microscopy for surface characterization
TEM	Transmission Electron Microscopy for defect characterization
TOKAMAK	Magnetic confinement nuclear fusion system using a torus with too short life of the first wall
VGF	Vertical Gradient Freeze - a method of crystal growth for compound semiconductors (variant of Bridgman)
YAG	Yttrium Aluminum Garnet - a common laser crystal usually doped with neodymium (Nd:YAG)
ZnO	Zinc Oxide
ZrO_2	Zirconium Dioxide - generally referred to as cubic zirconia

Worldwide no education of Crystal Technologists yet!

Inside Apple's broken sapphire factory

THE WALL STREET JOURNAL NOVEMBER 20, 2014 9:49AM

SHORTLY before 7am Pacific time on October 6, the chief executive of GT Advanced Technologies called an Apple vice president with bad news: **GT, which was to supply Apple with superhard sapphire screens for its new iPhones, had filed for bankruptcy 20 minutes earlier.**

The filing surprised Apple, because the companies had been negotiating changes in their contract to ease GT's financial strain, according to a letter Apple later sent to GT's creditors. Executives of the companies had planned to meet the next day at Apple's headquarters.

A year earlier, Apple and GT had hailed a $US 1 billion plan to build an Arizona factory that would produce 30 times as much sapphire as any other plant in the world.

Instead, the alliance turned into a rare — and public — misstep for Apple, whose strict management of its global supply chain has helped it become the world's biggest company by market value.

Apple co-founder Steve Wozniak takes new role. How Office is stuck in the PC era.

iOS update promises better iPhone 4S and iPad 2 performance

From the making of the first iPhone in 2007, Apple repeatedly has pushed its suppliers to achieve the improbable, while driving hard bargains on price and time to market.

The Apple-GT marriage was troubled from the start. GT hadn't mass-produced sapphire before the Apple deal. The New Hampshire company's first 262-kilogram cylinder of sapphire, made just days before the companies signed their contract, was flawed and unusable. GT hired hundreds of workers with little oversight; some bored employees were paid overtime to sweep floors repeatedly, while others played hooky.

GT's meltdown underscores the promise and peril for Apple suppliers. An Apple deal can generate billions in revenue. But it also means adapting to huge fluctuations in demand, at razor-thin profit margins and little room for error.

GT Chief Operating Officer Daniel Squiller told the bankruptcy court that Apple had turned his company into a captive supplier, "bearing all of the risk and all of the cost". GT couldn't make a profit at Apple's "dictated pricing," he said.

Apple put blame for the deal's failure "squarely at the feet of GTAT's own management," according to the letter to GT's creditors, which Apple allowed The Wall Street Journal to review. "We never wavered from our commitment to make the project successful."

The Cupertino, California company turned to GT while seeking to solve a big problem with iPhones: scratched or broken screens.

GT spent $US 900 million — more than twice the $US 439 million Apple provided — to get the sapphire factory up and running.

Sapphire is one of the hardest materials on earth, now typically produced synthetically, in furnaces that reach more than 1,980 degrees Celsius. It also is expensive — more than five times the cost of glass.

Apple consumes one-fourth of the world's supply of sapphire to cover the iPhone's camera lens and fingerprint reader. Early last year, the company began looking for a much larger supply, to cover the iPhone's screen.

GT made furnaces for producing sapphire. According to Apple's letter to the creditors, GT told Apple in March of last year that it was developing a furnace that could produce a sapphire cylinder, known as a boule, weighing 262 kilograms, more than twice as large as what were then the biggest boules. The larger boule would yield more screens, reducing costs.

GT said in its bankruptcy filings that Apple expressed interest in buying 2,600 of the new furnaces.

Around early summer, Apple switched gears and asked GT to make the sapphire. Apple didn't want to pay GT's typical 40 per cent margin for the furnaces, a person close to GT's operations said.

Apple also was having trouble finding a sapphire manufacturer. An executive at another company Apple approached last year said it couldn't make a profit producing sapphire at the price Apple wanted.

Apple offered to lend GT $US 578 million toward building 2,036 furnaces and operating a factory in Mesa, Arizona. Apple would buy and retrofit the factory for an additional $US 500 million and lease it to GT for $US 100 a year.

GT was intrigued, because the agreement would provide more consistent revenue than equipment orders. Moreover, GT's business making equipment for solar cells had fallen on hard times. GT's 2013 revenue was down 66 per cent from two years earlier.

On October 31 of last year, GT and Apple signed an agreement, a few days after the first boule emerged from a GT furnace. The cylinder was cracked so badly that none of the sapphire was usable, people familiar with Apple's operations said.

GT said the quality would improve, and Apple was encouraged by GT's track record of making successively bigger furnaces, the people said.

GT quickly set out to hire 700 staffers. Hiring moved so quickly that at one point in late spring, more than 100 recent hires didn't know who they reported to, a former manager said. Two other former workers said there was no attendance policy, which led to an unusual number of sick days.

GT managers in the spring authorized unlimited overtime to fill furnaces materials to grow sapphire. But GT hadn't built enough furnaces yet, so many workers had nothing to do, two former employees said.

"We just kept sweeping the floors over and over," one of the former employees said. "I just saw money flying out the door."

Producing sapphire proved to be the biggest problem. It took roughly 30 days and cost about $US 20,000 to make a single boule. The people familiar with Apple's operations said more than half the boules were unusable.

GT stored unusable cylinders in rows in an area of the Mesa factory that employees labeled the "boule graveyard," people close to GT's operations said.

Mr. Squiller, the GT operations chief, told the bankruptcy court that GT lost three months of production to power outages and delays building the facility.

Apple was responsible for building the facility to GT's specifications and providing power. Apple told the creditors that GT failed because of "mismanagement," not power interruptions.

Apple's comments were "purposely misleading, out of context or inaccurate," GT said in a brief statement for this article. "There is no point in engaging in a point-by-point debate on each issue."

Late this April, Apple withheld the final $US 139 million it was supposed to advance GT, saying it hadn't met the contract's output or quality requirements.

GT said in its bankruptcy filing that Apple repeatedly changed specifications for the sapphire. The filing said GT spent $US 900 million — more than twice the $US 439 million Apple provided — to get the factory up and running.

On June 6, GT Chief Executive Thomas Gutierrez met with two Apple vice presidents in Cupertino to explain the production problems, according to Apple's letter to the creditors. He presented a document titled "What Happened," listing 17 problems, including improperly stocking the furnaces and creating problems by inadvertently changing a furnace design.

Mr. Gutierrez said he was there to "fall on his sword," the Apple letter said. After the meeting, GT decided to stop producing 262-kilogram boules and make 164-kilogram cylinders to get the formula right.

When a boule was suitable, GT used a diamond saw to carve 35-centimetre thick bricks in the shape of Apple's two new phones: the iPhone 6 and iPhone 6 Plus. Those bricks would be sliced lengthwise to make screens.

Manufacturing wasn't the only problem. In August, one of the former workers said, GT discovered that 500 sapphire bricks were missing. A few hours later, workers learned that a manager had sent the bricks to recycling instead of shipping. Had they not been retrieved, the misfire would have cost GT hundreds of thousands of dollars.

By that point, it was apparent that sapphire wouldn't be used for the screens on the new iPhones, which went on sale September 19.

Yet Apple still was eager to get as much sapphire as possible, the people familiar with its operations said. Apple's letter said it only received 10 per cent of the sapphire that GT originally promised.

The people close to GT's operations said contractors for Apple applied quality standards inconsistently, sometimes accepting bricks that had been rejected a few days earlier.

In the first week of September, GT told Apple that it was having significant cash-flow problems. It asked Apple to pay the final $US 139 million loan installment and asked Apple to pay more for sapphire deliveries starting in 2015, one of the people familiar with GT's operations said.

On October 1, Apple offered to give GT $US 100 million of the $US 139 million loan installment and delay the repayment schedule, the people familiar with Apple's operations said. Apple also offered to raise the price it paid for sapphire this year, to discuss raising it for 2015 and to relax exclusivity agreements so GT could sell furnaces to other customers, they said. The companies agreed to discuss the offer in person October 7 in Cupertino.

Then came the early-morning October 6 call, when GT chief Mr. Gutierrez told Apple that his company had sought bankruptcy protection. The people close to GT's operations said executives hadn't told Apple about the bankruptcy plan because they feared Apple would try to thwart them.

GT shares collapsed 93 per cent on the news, wiping out roughly $US 1.4 billion in market value.

(Product photos from the GT Advanced Technologies website showing Synthetic Sapphire. Source: Supplied)

The Wall Street Journal

Consequences:

- *GT tries to sell 2036 HEM furnaces (578 million USD)*
- *Apple will use the facilities in MESA/Arizona for a Data/Management Center with 179 employees*
- *No sapphire window for Apple i-Phone6 and i-Pone 6Plus*

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Report for the American Association of Crystal Growth (AACG) Newsletter /F.J. Bruni 4/2013

Crystal Technology Education for Energy, Water, Health, Security & Novel Technologies

Crystal Technology, the synthetic crystal and epilayer production including crystal machining and required design and construction of equipment, forms the foundation of the modern electronics revolution and underpins all aspects of global commerce, communication, energy production and medical technology. It is fundamental to the advances in electricity production, transport and storage that will be critical to improving energy technologies to reduce the impact of energy on global climate change.

At the invitation of Dr. Hans Scheel, a group of experienced technologists in this field from Europe, Asia and the United States, convened for a meeting for a week in Poulithra, Arcadia, Greece in May 2012 to discuss the need for the requisite education and training of future engineers and scientists who will form the first generation of crystal technologists specifically trained with the basic knowledge of crystal materials technology (CMT) enabling the CMT engineers to consult and collaborate with leading specialists of related scientific fields.

The goal of the meeting was to generate a WHITE PAPER outlining the need for this training regimen as well as to include the recommended training courses on both the undergraduate and graduate levels. This White Paper will be circulated to leaders of industry, government and academia with the goal of promoting this specialized training in universities and engineering schools.

Among those present, in addition to Dr. Scheel, were Prof. Alexey Borodin, EZAN Chernogolovka, Russian Academy of Sciences; Prof. Thierry Duffar, Professeur à l'Université de Grenoble, France; Dr. Frank Bruni, Consultant, California, USA; Prof. Klaus Jacobs, GaN Project Berlin, Germany; Prof. Koichi Kakimoto, Institute of Applied Mechanics, Kyushu University, Japan; Prof. Georg Roth, Institut für Kristallographie, RWTH Aachen, Germany; Prof. Yasuhisa Sano, Dept. of Precision Engineering, Osaka University, Japan; Prof. Brian Tanner, Durham University and Kromek Company, UK; Prof. David Witter, Anaxtal Inc., South Carolina, USA; and Prof. Kazuto Yamauchi, Dept. of Precision Engineering, Osaka University, Japan.

Between technical sessions, presentations and discussions, Dr. Scheel and his wife, Regula Hauser Scheel, organized tours of historical archeological sites including Olympia, Epidauros, Mycenae and Athens. (A ladies program which ran in parallel with the technical sessions enabled those wives in attendance to see additional sites of interest). The meeting was held at the Smyros Resort close by to the winter home that Hans and Regula maintain in Greece on the Aegean shore.

All costs of the conference including meals, housing, day trips and excursions (other than travel to Greece) were subsidized by Dr. Scheel using retained revenues from previous workshops on crystal growth and technology which he had organized in Switzerland. In this way the proceeds of the previous workshops could be dedicated specifically to the advancement of crystal technologist education.

Dr. Bruni (and his wife) returned to Greece in March and with Dr. Scheel is in the final stages of editing the WHITE PAPER and hopes to have it ready for circulation by the end of spring.