AC 2010-471: DEVELOPMENT OF THE LABORATORY-BASED COURSE IN LEAN SIX SIGMA NANOMANUFACTURING

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Development of a Laboratory-Based Course in Lean Six Sigma Nanomanufacturing

Abstract

We are developing a laboratory- and project-based Lean Six Sigma Nanomanufacturing course under an NSF Course, Curriculum, and Laboratory Improvement Grant, Type 1. The laboratory- and project-based course will teach Applied Engineering Technology (AET) students nanomanufacturing by combining hands-on nanotechnology laboratory experiments and Six Sigma analysis with lectures on Lean manufacturing principles and implementation. AET students will be introduced to nanotechnology principles, projects, and laboratory procedures by working with leading faculty members through classroom instruction, guest lectures, and field trips. During an 11-week term, the following laboratory projects will be implemented to simulate nanomanufacturing processes: production of CdSe quantum dots; electrodeposition of magnetic Ni nanowires; fabrication of organic LEDs; and fabrication of TiO_2 nano solar cells. The laboratory experiments will be supported by various analytical techniques, such as fluorescence and electron microscopy; Raman and UV absorption spectroscopy; dynamic light scattering; optical transmission and reflection measurements; and atomic force microscopy, among others. Analysis techniques will generate suitable data sets for quality engineering and statistical process control using Lean Six Sigma methods. The course will be developed in the format of educational modules. Selected modules will become available to community colleges collaborating with Drexe University, as well as middle and high schools through outreach programs supported by the Drexel's AET faculty and staff.

Introduction and Objectives

Lean Six Sigma approaches represent the state-of-the-art in manufacturing operations. The combined disciplines of Six Sigma Quality Management[1-6] and Lean Operations[7-9] can be applied to a nanotechnology laboratory - and project - based course to teach modern industrial engineering and quality control principles as applied to nanomanufacturing. The intended audience is Applied Engineering Technology (AET) students, as well as other undergraduate science, engineering, and technology majors. The course is comprised of laboratory tasks and projects to synthesize and characterize nanomaterials, such as quantum dots and nanowires; and to fabricate and evaluate nanoscale devices, such as nanocrystalline solar cells and organic LEDs. Laboratory projects simulate nanomanufacturing operations, and are structured in a Six Sigma framework, wherein methods of Six-Sigma Quality Assurance and Process Optimization are made an integral part of the course. The laboratory and its operation are organized on Lean Principles of production.

Our educational objectives are four-fold:
1. To introduce students to nanotechnology, including hands-on experience with synthesizing nanomaterials and fabricating nanodevices;
2. To instruct students in analytical methods to characterize, assess, and qualify these nanomaterials and devices;
3. To teach Six Sigma quality methods as applied to nanomaterials, processes, and devices;

4. To expose students to the principles of Lean Manufacturing in a laboratory setting that simulates a small manufacturing enterprise performing low-volume, high-product-mix production.

Background

There is a broad consensus that in the next several decades, nanotechnology will form the basis of a second industrial revolution. It was estimated several years ago that there were more than 4000 research centers and companies involved in nanotechnology.[10] Many educational institutions are offering courses, laboratories, concentrations, majors, and programs in nanotechnology and allied fields. Most of these appear to focus on basic nanoscience discoveries and applications, with relatively little emphasis on translating R&D to the factory floor. Nevertheless, manufacturability, process scale-up, and quality assurance are pressing issues that may limit nanotechnology progress. "The challenge facing researchers, technologists, and manufacturers is whether the same well-trodden path taken to commercialize macroproducts can be used for products based on a combination of micro- and nanotechnologies."[11]

AET graduates have traditionally played an important role in manufacturing, both as industrial engineers and manufacturing process engineers. AET graduates are also prominent as quality assurance and R&D specialists. In view of the increasing importance of nanotechnology, applied engineering and other technology students need a good grounding in basic nanoscience and applications, as well as in characterization methods and tools. Moreover, in addition to Industrial Engineering subjects, such as Lean Six Sigma, other disciplines, such as Concurrent Engineering, Design for Manufacturability, Rapid Prototyping, and Plant Operations, need to be integrated into AET education. This curriculum 'overload' provides incentive to develop courses that bring together broader educational objectives and various disciplines in an integrated, streamlined form. To this end, the Lean Six Sigma Nanomanufacturing course combines instruction and practice in nano materials and devices, characterization techniques, and Lean Six Sigma methods and principles.

Approach

Our approach is to adapt already-developed and widely-disseminated educational nanotechnology laboratory projects for teaching Lean Six Sigma methodologies. These labs have well-documented protocols, including on-line videos and supplemental information. They avoid highly toxic materials and utilize either low-cost, commercially available kits, or other readily-available materials. These laboratory exercises simulate a pilot manufacturing process to produce a nanomaterial or nanodevice with the aim of generating quantitative data that provides instructive case studies to teach Six Sigma techniques. Further, Lean principles can be implemented in the laboratory and its operation, thus providing students with exposure to modern manufacturing disciplines.

The Lean Six Sigma format described here is sufficiently generic that it can be adapted for many different types of nanotechnologies. Most of the labs, as originally developed, require one or two several-hour laboratory sessions to complete, but the addition of Six Sigma tasks will add several hours to each lab project. Alternatively, if time is limited, the lab synthesis and/or characterization can be done as a demonstration and students can analyze data with Six Sigma methodologies. Supplemental lectures on Lean Six Sigma accompany the laboratory work.

The underlying theme is that production processes have inherent variation that impacts material properties and device performance. The primary aim of the laboratory is for students to identify the main controlling experimental parameter(s) of a specific property or device feature, and reduce its variation. Six Sigma provides a framework for applying organizational and statistics-based methods for controlling and reducing process variation. Six Sigma includes a Quality Function Deployment task to prioritize features of a product or process that add value for the customer. In general, the laboratory projects involve materials synthesis and device fabrication comprised of several processing steps. Each step has one or a few parameters that can be quantified and measured. Measurement Systems Analysis, and in particular Gage Repeatability and Reproducibility[12] studies, can validate the measurement techniques. The importance of a particular processing variable is often not immediately obvious. Students can perform a Design of Experiments (DOE) study to investigate the relative weight of different process input variables with respect to their impact on a process output variable. Ideally, a process variable will exhibit a normal (Gaussian) distribution, from which process capabilities can be derived.

Six Sigma Implementation

Six Sigma is a systematic "data-driven" program to reduce variation and build quality assurance into processes. Six Sigma was pioneered by Motorola in the 1980s, and has become widely established in numerous manufacturing and service enterprises. The name *Six Sigma* refers to the ultimate goal of reducing variability in a process such that the specified tolerance window spans six standard deviations of a particular process variable. Six Sigma serves as a structured problem solving methodology that provides a 'toolbox' of management, analysis and statistical techniques to improve quality. A Six Sigma program is organized in stages according to DMAIC: Define (the problem and objectives), Measure (the relevant process characteristics), Analyze (the data), Implement (or Improve the Process), Control (the process to maintain the gains). Some of the Six Sigma methods used in these stages that are applicable to the laboratory projects described here are summarized in Table 1.

Table 1: Six-Sigma Toolbox: Phases of a Six Sigma Program and Methods

Design	**Measure**	**Analyze**	**Improve**	**Control**
QFD SIPOC Process Mapping	Pareto Charts Histograms Process Capability GR&R	Hypothesis Testing: • T-tests • Tests for Equal Variance • Chi Square	Hypothesis Testing: • ANOVA • Non-Parametric Tests Design of Experiments	Visual Process Control Control Charts Mistake-Proofing

Quality Function Deployment (QFD). QFD is a method for designing a product or service according to customers' needs. More specifically, QFD is a tabulation technique that is implemented through a series matrices that translate customer demands and needs into product or product specifications. In this way, the customer's value-added features are deployed in terms of measurable quantities.

Critical-To-Quality (CTQ) and Yield, Process Capability Indices. In process measurements where a tolerance can be specified and a standard deviation estimated, various metrics and indices can be calculated to ascertain a baseline for processes and measure improvements.

Measurement System Analysis: Gage Repeatability and Reproducibility (GR&R) Studies. Gage R&R provides statistical techniques to assess the accuracy, precision, stability, and linearity of measurement methods, and in particular, allow the separation of measurement effects variations attributed to instruments, operators, and process.

Descriptive Statistics. As part of their Laboratory Reports, students are instructed in descriptive statistics to summarize their data including histograms, Pareto analysis, scatter plots and correlation diagrams.

Regression Analysis, Hypothesis Testing, and ANOVA. Quantitative process improvement begins with establishing functional relationships between output process variables in input process variable. In each lab, there are at least several experimental parameters that can be tested and correlated for their effect on a measurable output.

Design of Experiments (DOE). Design of Experiments is one of the most powerful tools for Six Sigma. For this course, the third and/or fourth labs are good opportunities to identify four of five candidate process variables that can be subjected to a DOE process study. Many software packages for DOE are easy to learn and can be incorporated into the course. For example, a 45-day trial version of Design-Expert DOE software is available from http://www.statease.com/.

Lean Principles

Lean refers to a management philosophy and methods of organization and operation, and as such, it is more difficult to capture its essence in a laboratory setting, compared to Six Sigma. Lean principles are generally subtle and their full impact is more evident in a production environment. Still, many components of Lean manufacturing can be demonstrated or simulated in a laboratory. As part of the instruction in Lean and Six Sigma, the nanomanufacturing laboratory-based course features assigned topical readings, lectures, presentations, and discussion with the students.

Lean Manufacturing is based on approaches pioneered by Toyota ("Toyota Production System") for automobile manufacturing operations that eliminate waste and non-value-added activities. Lean encompasses Just-in-Time (JIT) methods that focus on reducing inventory, *Jidoka* or building quality into processes, and Single-Minute Exchange of Die (SMED) techniques that enable quick changeover of production tools to facilitate flexible production schedules for low-volume, high-product mix manufacturing. Lean principles have been applied to a wide variety of operations, both in manufacturing and in service industries such as healthcare. Many Lean concepts are best taught through case studies or simulations of commercial operations.

While it is relatively straightforward to apply Six Sigma methods to laboratory projects since Six Sigma includes a host standard statistical and quality assurance techniques for data analysis, the introduction of Lean Principles is more challenging. For our purposes, we are adapting Lean methods as implemented in two venues:

1. The small machine shop (or job shop) that focuses on low-volume, high-mix manufacturing;
2. The analytical laboratory, including clinical and quality assurance labs.[13,14]

These two applications should reflect many of the issues that will come to fore in nanomanufacturing. Our approach is to organize the laboratory and projects that simulate nanomanufacturing efforts according to Lean principles as discussed below.

Eliminating Waste. Lean identifies the following types of waste: overproduction, excess inventory, waiting, transport or conveyance, overprocessing, unnecessary motion of people, machinery, or product, and correction or rework of defects. These operations do not add value to the final product, and many of them can be mitigated by re-organization of the production area, which in this case refers to the laboratory.

Cellular Layout. The laboratory for the course is set up as cellular manufacturing layout. Each step in the laboratory protocol (including measurements and analysis) is arranged sequentially according to process flow, with stations in close proximity. The students make "spaghetti" or work-flow diagrams (using the floor plan of the lab) as part of their lab reports.

Kanban. The *kanban* system is used to manage the flow of material or product through the factory. Kanban is one of the main components of the visual workplace.

Workplace Organization ("The 5-S's"). The production/laboratory area is maintained according to the 5-S's: Sort, Set In Order, Shine, Standardize, and Sustain.

Poke-Yoke (Mistake Proofing). Techniques for mistake proofing in laboratory settings have been described by Hinckley.[15,16]

Characterization and Analysis

The range of Six Sigma tasks that can be applied to the various nanotechnology laboratories will depend on the availability of analytical tools for measurement and characterization. While the synthesis and fabrication of the nanomaterials described in the laboratory projects here requires only modest resources and facilities, schools may have limited access to analytical instruments or facilities. In particular, more expensive instrumentation such as electron microscopy may not be available, or it may be impractical to give students access to such sophisticated instruments. Moreover, part of the development of quality assurance is to determine which measurements provide meaningful tools for statistical process control and process diagnostics. Laboratory experiments described here can be done with a UV/visible spectrophotometer/fluorimeter (as commonly found in undergraduate chemistry labs), a Raman spectrometer, electrical measuring instruments such as a multimeter, a CCD camera, and various types of optical microscopes. Another option for the instructor is to generate electron microscopy images and/or X-ray diffraction data sets that students can analyze as part of their out-of-class assignments.

Laboratory Projects

1. Synthesis of CdSe Quantum Dots

Quantum Dots (QDs) are semiconductor crystals with characteristic dimensions of 1 to 10 nm, and which exhibit strong room-temperature fluorescence. The absorption and emission wavelength depends on the size of the QD. QDs and other colloidal nanoparticles find application in bioassays and medical imaging[17,18] as well as solar cells and light-emitting diodes (LEDs). As such, QDs provide a good example of process control of a nanoscale dimension and its impact on a useful property—fluorescence emission wavelength. Boatman[19] describes a relatively safe, easy, and fast synthesis of CdSe quantum dot nanocrystals as colloidal suspensions, which can be readily analyzed by absorption and emission spectroscopy. Their method avoids the use of highly toxic and/or pyrophoric compounds prescribed in other protocols for synthesizing quantum dots, and does not require inert atmosphere working conditions, such as a glove box with controlled ambient. The CdSe QD nanocrystals are made from CdO and elemental Se using a kinetic growth method where QD size depends on reaction time. Students prepare a precursor stock solution of elemental Se in 1-octadecene and trioctylphosphine, and a Cd precursor solution of CdO in oleic acid (a surfactant) and octadecene. The Cd precursor solution is heated to 225 °C in a round bottom flask clamped in a hearing mantle, whereupon Se precursor solution is added to initiate the reaction that precipitates colloidal CdSe nanocrystals. Samples of 1-ml in volume are pipetted from the reaction mixture at frequent time intervals (~30 seconds) and quickly cooled to quench the reaction. About nine to ten samples are collected, and the reaction time is recorded for each aliquot. Each of the samples will exhibit a characteristics color, indicating a variable product range according to reaction time (Figure 1).

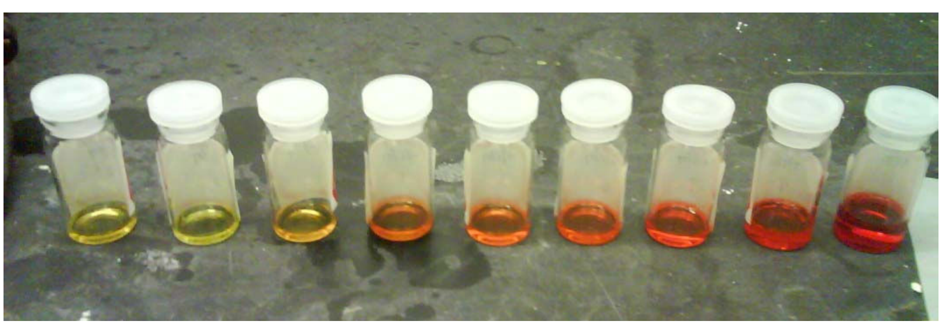


Figure 1. Colloidal suspensions of CdSe Quantum Dots.

For quantitative analysis, the emission and absorption spectra of the QD colloidal suspensions can be measured in a spectral photometer/fluorimeter. A figure of merit for QDs is a narrow fluorescence emission spectra, and the FWHM (full-width, half maximum wavelength range) can be regarded as a quality metric. This measurement is amenable to a Gage R&R study.

As an exercise in regression analysis, the students can correlate absorption wavelength maxima with emission wavelength maxima (see Figure 1 in reference 19). Another correlation is emission wavelength peak vs. reaction time, with the objective of demonstrating control of a nanoscale property through a process parameter (reaction time), as well as inherent product variation (spectral emission width.)

A simpler laboratory based on the synthesis of silver nanoparticles is also feasible.[20] A colloidal suspension of 12-nm silver nanoparticles can be made by reducing aqueous silver nitrate with excess sodium borohydride solution. Although metal nanoparticles do not fluoresce like semiconductor quantum dots, they do exhibit a characteristic optical absorption spectrum. Transmission electron microscope (TEM) images can be used to measure the size of the silver nanoparticles which exhibit an approximate normal distribution (see Figures 3 and 4 in reference 20) with mean of 12 nm and standard deviation of 3.4 nm. The electron microscopy can be done for the students, who then work from TEM images which are examined visually using a scale marker included in the image, or using image processing software. This data can be used to analyze normally-distributed process variables.

2. Template Synthesis of Nickel Nanowires

Nanowires (cylindrical structures with nanometer-sized crosss-sections) have applications in electronic, optical, magnetic, and mechanical devices,[21,22] including solar cells and nanoelectronic power sources.[23] In this laboratory, students synthesize and characterize nickel nanowires that exhibit useful magnetic properties. The nanowires are made by a simple electrochemical template synthesis method.[24] This method has been used in undergraduate nanotechnology courses at the University of Wisconsin and other educational institutions.[25] A straightforward application of such nanowire suspensions as magneto-optical switches has also been described.[26] Briefly, nanowires are fabricated by electrochemical deposition of nickel in nano-sized channels of an alumina or polycarbonate porous membrane (Whatman nanopore membranes). One side of the alumina membrane is painted with a gallium-indium eutectic to form a cathode contact. The nickel plating process is done in a 50-ml beaker with a commercial nickel plating solution, a nickel wire anode, and a battery or dc power supply as the voltage source. The electroplating area can be defined by partially masking the substrate with tape. After the deposition step, the membrane template is then dissolved in 6M sodium hydroxide to yield a suspension of free nickel nanowires. The nanowires can be washed and resuspended in various solvents including water, ethylene glycol, and glycerol. The nanowire synthesis part of the lab takes about 90 minutes.

The nanowires are examined by drying out a drop of nanowire suspension on a glass microscope slide. The wires are visible under a low power optical microscrope, and their images are captured with a CCD camera mounted on the microscope for subsequent analysis. The analysis of the nanowires is facilitated by using an external magnet to align the nanowires during the drying step. Scanning electron microscope (SEM) images provide greater detail and resolution. In this lab, we regard the primary output process variables as the distribution of nanowire lengths (mean length, range, and standard deviation) as controlled by the process input variable plating time. Bentley[25] presents examples of optical microscope and SEM images of the nanowires, and the relationship between nanowires and deposition time, as well as additional characterization by

X-ray diffraction of the wires still embedded in the template membrane, indicating a preferential orientation of the nanowire growth direction. A more detailed study of nickel electroplating variables (plating solution composition, plating temperature, and pH) is described by Schonenberger[27] and Rahman.[24] This lab project can be extended to demonstrate applications of the nanowires as magneto-optical switches,[25] in which case switch device performance (modulation depth and switching speed) could be used as figures of merit for process improvement.

3. Organic Light-Emitting Diodes

Solid-state electroluminescent devices are an area of considerable technical and commercial interest for applications to lighting, consumer products, and displays. Light-emitting diodes (LEDs) can be made from thin films of organic materials that are 60- to 100-molecules thick[28,29], such as from a solid film of tris(2,2'-bipyridine) ruthenium(II) complex deposited on indium tin oxide-coated glass substrate.[30, 31] These experiments were successfully used in Massachusetts High Schools and undergraduate materials science courses (MIT). The operation of the LED is based on charge injection under voltage bias, charge transport by electron hopping and ion migration, and decay of an energetic ruthenium complex that emits red-orange light at 630 nm wavelength.

This laboratory project (and the following laboratory on nano solar cells) has educational interest on several counts:

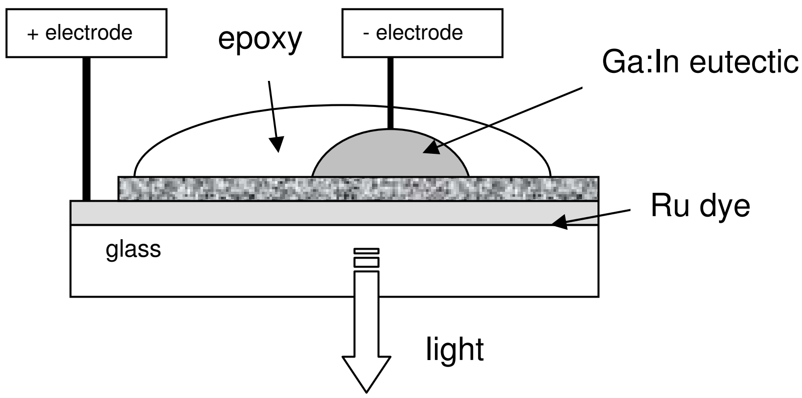
- It utilizes nano-scale structures,
- It involves several sequential processing steps each with at least several controlling variables,
- Its end product is a device with well-known consumer applications and straightforward figures of merit quantitating its performance,
- The devices have some stability or reliability issues characteristic of many emerging nanotechnologies.

Accordingly, nano LEDs and solar cells are good case studies for illustrating various aspects of nanomanufacturing and the application of Lean Six Sigma. The LED are made by spin-coating an aqueous ruthenium complex ($[Ru(bpy)_3]Cl_2$) mixed with a polymer (polyethylene glycol) on glass slides (http://www.mrsec.wisc.edu/Edetc/nanolab/oLED/). The glass slides are pre-coated with a conducting, transparent indium tin oxide that serves as a cathodic electrode and are commercially available (Hartford Glass Co., Hartford, IN). Small droplets of indium-gallium (liquid) eutectic are dabbed onto the Ru-coated substrate to make an anodic contact. The deposition areas can be defined by partial masking with tape. The spin coater used to deposit the Ru-containing solution is fashioned from a small electric cooling fan (such as found in desktop computers) run by a low-voltage dc power supply.

LEDs are testing by probing (Figure 2). The LEDs are generally short-lived (lifetime measured in minutes or hours), primarily due to the effects of humidity/oxidation. Thus, lifetime studies offer another opportunity for statistical analysis. Some relevant process variables include the concentration of the Ruthenium solution and the PEG (polyethylene glycol), the spin speed coater speed (rpm), the amount of solution applied in the spinning process, and the sheet conductivity of the indium tin oxide layer. These process variables can be studied by Design of Experiments (DOE).

We modified this laboratory by making the LEDs on a custom printed circuit board[32] in order to produce an array of individually-addressable LEDs. This was done in the interest of generating more LED replicates (~16-20) for statistical analysis. The LED array output can be monitored with a CCD, and maps of pixel intensities can follow the variation in array elements and the reduction in light output over time.

(a)



(b)

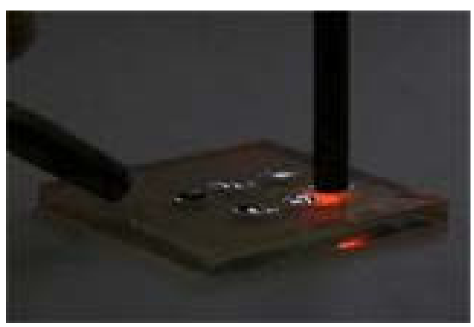


Figure 2. (a) Organic LED cross section schematic, (b) testing of organic light-emitting diodes.

4. TiO_2 Nanocrystalline Solar Cells

Photovoltaic solar cells based on nanomaterials are an important application of nanotechnology to renewable energy.[33] As a specific example, organic dye-sensitized TiO_2 nanocrystalline solar cells demonstrate the utilization photosynthesis-like electrochemical processes to solar generation of electrical power, and are the focus of much pure and applied research in nanomaterials and devices.[34,35] Commercialization of similar kinds of solar cells is under way.[36] This type of cell has been well developed as an educational case study of nanomaterials.[37-39]

In this experiment, and as with the previous organic LED laboratory, glass slides with a transparent conducting indium tin oxide coating can be purchased or prepared by vacuum deposition operations. The slides are coated with a colloidal solution of TiO_2 nanoparticles (Figure 3), and then sintered in an oven. Next, the TiO_2 coating is stained with natural dyes, such as derived from plant material by soaking the TiO_2-coated substrate in a dye solution. A second conductive oxide-coated glass slide is coated with carbon using a pencil or graphite rod. The two glass slides are then clamped together to form a solar cell. The solar cell area can be defined by masking the substrates with opaque tape.

A solar cell provides many easily-measured performance metrics, several of which are diagnostic for specific device faults and material quality. These include open-circuit voltage, *I-V* curve shape or fill factor, photogenerated current, diode ideality factor, conversion efficiency, series resistance, shunt resistance, and most revealing: spectral response or quantum efficiency, i.e., the solar cell photocurrent as a function of incident light wavelength. Most of these parameters can be measured with a multimeter or curve-tracer instrument. A monochrometer, white light source with color filters, or different color LEDs can be used to generate approximate monochromatic light for spectral response measurements. Like the organic LEDs described above, these solar cells also have stability issues that can be quantified and optimized using Six Sigma.

As a Six-Sigma case study, this experiment provides a comparatively large parameter space to explore process optimization. These variables include the sheet resistivity of the conductive oxide layers coating the glass slides, the thickness of the TiO_2 layer, the concentration and soak time for the dye agent, and the thickness of the carbon layer.

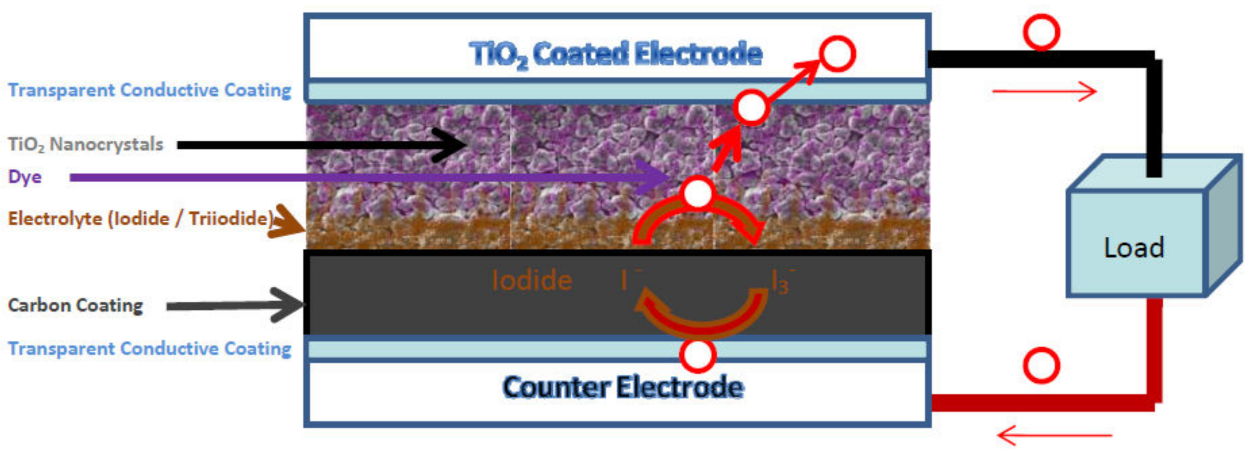


Figure 3. Cross-section of TiO_2 nanocrystalline solar cell.

Course Structure

A three-credit eleven-week (within Drexel's quarter system) laboratory- and project-based course was developed. Fifteen hours are devoted to laboratory work and fifteen hours to lectures on nano-processes that are the basis of the lab work, Six Sigma topics, ethics and sustainability, and nano entrepreneurship. Guest lecturers are planned for the classroom sessions.

Students can replicate a pilot production process that turns a raw feedstock into a useful nanotechnology product, such as organic light-emitting diodes and nanocrystalline solar cells.

Each process step is characterized, either by *in-situ*, real-time methods or by analysis of samples of intermediary or final product. These measurements generate data for Six Sigma analysis and statistical process control, including Lean methodologies. The final presentation is scheduled during the eleventh week. The course structure is presented in Table 2.

Table 2. Course Structure: Lean Six-Sigma Nanomanufacturing.

Week	**Time**	**Topics/Labs**
Week 1	2 hours 1 hour	Lecture: Introduction to Nanotechnology Lecture: Introduction to Six Sigma
Week 2	1 hour **3 hours**	Lecture: Measurement Systems Analysis Laboratory Safety and Lab Orientation **Lab 1: Synthesis of CdSe QDs**
Week 3	2 hours 1 hour	Lecture: Six Sigma Data Analysis Lecture: Materials Characterization
Week 4	**4 hours**	**Lab 2: Template Synthesis of Nickel Nanowires**
Week 5	2 hours	Lecture: Design of Experiments
Week 6	**4 hours**	**Lab 3: Organic LEDs**
Week 7	1 hour 1 hour 1 hour	Lecture: Regression, Hypothesis Testing Lecture: Statistical Process Control Lecture: Lean Principles
Week 8	2 hours **2 hours**	Lecture: Lean Manufacturing, Part 1 **Lab 4, Part 1: Nanocrystalline TiO_2 Solar Cells**
Week 9	**2 hours** 1 hour	**Lab 4, Part 2: Nanocrystalline TiO_2 Solar Cells** Lecture: Applied Statistical Methods
Week 10	3 hours	Lecture: Lean Manufacturing, Part 2
Week 11	3 hours	Final Presentation

Summary

This paper is an interim report of our ongoing development of a laboratory-based course on Lean Six Sigma Nanomanufacturing. We have successfully adapted various nanoscience laboratory exercises previously developed, tested, and disseminated at a host of schools and universities in the U.S. The adapted material is presented as case studies related to nanomanufacturing. The laboratory projects are modified to simulate nanomanufacturing processes that are amenable to Six Sigma analysis and process improvement. Based on the successful application of Lean Principles to Job Shops and clinical laboratories as described in detail in various literature sources cited, we believe an educational science laboratory, such as used for the undergraduate experiments described here, can also be a showcase of Lean organization and operation. The course satisfies several diverse educational objectives including both traditional Engineering and Technology curricula aims related to applied statistics and manufacturing operations, as well as newer goals such as nanotechnology, Six Sigma, and Lean approaches to production.

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