



“Paper Factory” produces a blend of science and engineering education

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You awaken at three in the morning to the sound of a shrieking child. As you stumble out of bed you wonder what could be wrong: Is your baby hungry, does he need to be changed, or is it something more, like a cold? This situation, so familiar to any new parent, might soon be solved by the use of “smart” diapers that incorporate flexible, paper-based electronic sensors to monitor health. These sensors can detect when a change is needed and track vital stats to one day predict the onset of sickness. “Smart” diapers are just one of the many paper-based projects being developed at the University of Cincinnati as part of an innovative laboratory class that bridges the gap between science and engineering education.

With so many exotic materials available, scientists have only recently turned their attention to the ancient material—paper. Paper offers many advantages over silicon substrates, including flexibility and a low cost; it is also easily adapted to printing, and benefits from readily available manufacturing techniques.* Andrew Steckl, Gieringer Professor and Ohio Eminent Scholar at the University of Cincinnati, thought that this broad range of desirable properties might make paper a valuable teaching tool. His Nanoelectronics Laboratory has recently been depositing organic electronic devices on paper for computing and biosensing applications, which got him thinking: Why not develop a special topics class for incoming graduate students to design

their own paper-based devices? Not only would the students be exposed to cutting-edge research and learn fundamental electronics skills, they would also be able to shepherd a project from idea to final product. Researchers in the field would be invited to give guest lectures, helping to build interest in and an awareness of the many uses of such a seemingly mundane material. This unique blend of science and product engineering excited Steckl, so he began planning his course, now called the “Paper Factory,” in the fall of 2013.

Since such a course had not been taught before, Steckl decided that he would need to define clear boundaries and expectations for the students. “This is not an open-ended project—they have to make something work in one semester ... it’s more like the way research and development is done in industry,” he explains. The students were offered project suggestions, but would otherwise have free rein to choose their own ideas, vetted by in-class discussions. The only other restriction was cost—a strict budget of \$50 would be enforced—and the students had to demonstrate a functioning product by the end of the course. For Steckl this was particularly important, “They had to bring it to class and show everyone how it works. It couldn’t be just something hidden in the lab.”

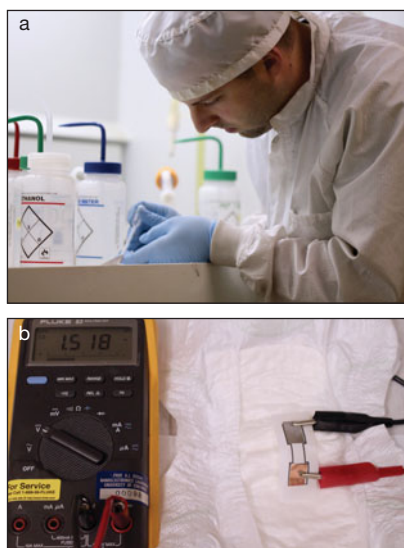
Taking advantage of so much freedom, the class pursued a wide array of imaginative project ideas. One group studied the design of the aforementioned “smart” diapers that can characterize waste products and record biometrics. This is of great interest to industry giants, such as Procter & Gamble and Kimberly-Clark, who are heavily invested in the multi-billion-dollar diaper market, and to start-ups who hope to break into the market with novel products. Materials selection for the diapers has proven to be difficult. Today, integrated circuits are typically formed on silicon



Steckl and his inaugural class of “Paper Factory” students.

Photo credit: Daewoo Han, PhD.

*For more details about paper-based technologies, see the *MRS Bulletin* April 2013 issue; www.mrs.org/bulletin.



(a) A “Paper Factory” study synthesizing a paper electrode. (b) A rudimentary smart diaper with a urine-powered battery and voltmeter. (c) One of Steckl’s students working on a “smart diaper.”

substrates and mounted onto printed circuit boards, which are composed of laminate composites of thermoset resin and copper. These substrates are rigid and silicon is expensive, greatly limiting their use in electronic garments.

To address this problem, PhD student Prajokta Ray designed a flexible, urine-powered electrochemical battery to provide power for various sensors in the diaper. Ray says that it was a challenge to choose materials within such a limited budget. She first had to identify different kinds of paper that might be used, analyze their surface topology to choose the best substrate, and then fabricate devices atop the paper. While difficult, she explains that this process showed her how real-world research is conducted. Ray says that “... the immense knowledge base I gathered and developed in this course has been most valuable for me. It has been a stepping stone [to my own doctoral research],” which now involves biosensing, microfluidics, and medical devices.

Steckl enlisted one of his postdoctoral research associates, Han You, to purchase supplies for the students and help them develop a reasonable time frame and goals for their projects. “Some of the projects proposed by the students turned out to be very difficult to complete within one semester, [so] I worked with them to adjust their goals to be able to complete

the project on time and on budget,” You explains. Because of the support from both Steckl and his assistants, most of the students’ projects were successful and only a few encountered difficulties. In one case, a student attempted to design an adhesive-backed portable weather sensor to detect local temperature and humidity. However, Steckl says that it was not possible to complete the project within the course’s budgetary constraints. “We tried to make it in a low-cost fashion, which proved to be a bit of a challenge. We didn’t really have enough time to make this fully successful, not because of any fundamental issues, but because we wanted to use very low-cost materials like printable inks.”

Steckl points out that, while the students were required to deliver a physical product at the end of the semester, he did make one exception. One of the students offered to assemble a digital library of relevant literature for the benefit of the entire class. This seemingly innocuous project soon proved to be an enormous undertaking, since many relevant search phrases other than “paper electronics”—such as “paper,” “composite,” and “cellulose”—are used in a variety of different contexts and fields. Because of this confusion, finding and categorizing all the appropriate literature was incredibly time-consuming. To avoid making the

problem any worse, Steckl himself has taken to referring to his group’s published works as “articles” instead of “papers,” and he encourages other researchers to be very specific in their terminology.

Thrilled by the enthusiastic student response, Steckl plans to reopen the “Paper Factory” again in the spring of 2016. Going forward he hopes that one of his students will expand on the digital library concept, eventually launching a website as a broader resource for scientists in the field of paper-based electronics. Asked about the most important lesson from his course, Steckl says that while many scientists conduct laboratory work, few actually learn what it takes to bring an idea all the way to a product in the marketplace. He believes that a course in which students are required to set goals, adhere to a strict budget, and deliver a final product can prepare them for the demands imposed on scientists today. This kind of integrative approach to teaching will only become more important as the traditional boundaries between science and industry continue to disappear.

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