Sensing Skins, from Molecules to Smart Cities:
A joint collaboration between Princeton and Todai

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Executive Summary

The vision: We are seeking to build a permanent collaborative program on what we call broadly “large-area electronics.” This is a new field of research with many potential applications in interfacing electronic systems with the physical world. In current technology, except for flat panel displays, the circuits of electronic systems are usually encased inside small black packages (integrated circuit) on circuit boards hidden away inside computers, cell phones etc. Our goal is a thin flexible “electronic skin,” with its surface covered in sensors and electronics. They could range from inches or centimeters in size to the size of buildings and bridges, to directly interface with the system of interest – people, buildings, etc. Being paper-thin and flexible, many types of applications are envisioned, from an electronic sensing “wallpaper” to flexible medical or neural implants to a structural element which senses the beginning of cracks in bridges.

Princeton and Tokyo are both leaders in the field, with largely complementary strengths. Princeton has a depth in the science of such structures and in the underlying principles for design principles which scale to very large size scales. Tokyo has a depth in practical aspects of making things “ultra-flexible” (like tissue paper) and in medical/animal applications and experiments. Both have many faculty and students involved, and both have strong external funding.

The high level goals of this proposal are (i) to build on existing efforts to deepen the intellectual engagement on a comprehensive and broad level between Princeton and Todai, and (ii) to do this through technical collaboration to advance the state-of-the art, and (iii) set the stage for a long-term joint program. By combining strengths, we plan to solve fundamental issues in how such large-area electronics are made, and show how these advances can affect people on multiple levels. After the three years, we plan to have a model for a permanent multi-faculty research and teaching collaboration between Princeton and Tokyo. This up and coming field will be an important for a long time; we want to lead it together.

Key Elements of our Partnership:

- Exchange of faculty, undergraduates, graduate students, postdocs, faculty, with visits from several days to a few months (total of 15 going each way each year).
- Joint teaching of undergraduate and graduate courses
- Eight faculty and their groups on each side
- A joint workshop for setting both a research vision as well as the model for the future Princeton-Todai relationship.

The plan is based on the multiple visits of Prof. Takao Someya to Princeton in the past 4 years as a Princeton Global Scholar and the shorter visits of several of us (Kahn, Wagner, Sturm) to Tokyo over that period. Together, we taught a joint graduate course we taught at Princeton when Prof. Someya was here in Princeton Spring 2010.
1. Faculty Participants

Princeton
Department of Electrical Engineering: Antoine Kahn, Barry Rand (as of July 1, 2013), James C. Sturm, Naveen Verma, Sigurd Wagner
Department of Chemical and Biological Engineering: Lynn Yueh-Lin Loo
Department of Civil and Environmental Engineering: Sigrid Adriaenssens, Branko Glisic

Todai
Department of Electric and Electronic Engineering: Takao Someya, Tsuyoshi Sekitani
Department of Bioengineering: Masaki Sekino
Institute of Industrial Science: Takayasu Sakurai
VLSI Design and Education Center: Makoto Takamiya
Department of Biomedical Engr., School of Medicine: Takashi Isoyama, Yusuke Abe, MD.
Department of Advanced Materials Science: Jun Takeya

2. Exchange Program

The heart of our program is exchanges of people to build mutual relationships, and to do research. We are all lab scientists, with differing lab capabilities. Students and postdocs are the ones in the labs on a daily level who actually do most of the hands-on work. Thus their exchange, to carry out experiments based on our joint capabilities, is critical to our plan.

Graduate Students: 2-3 each way per year. A typical stay may be two months, with a follow-on visit of two weeks to complete a publication. We anticipate that the physical arrangements will be easy to make, as the students will join existing research projects. Desk spaces are available on both sides, and accommodations are priced reasonably. In Princeton we plan to house graduate students in the Princeton Theological Seminary, where room rates start at $65/night, and in Tokyo visiting graduate students are accepted into the two guest on-campus houses of Todai, with a rate of $60/night. Post-docs may be included in this category.

Undergraduate Students: 1-2 each way per year. Research stays will be arranged for the vacation periods on either side. Visiting undergraduates will stay at the Forest Hongo Hotel, across the street from Todai’s campus, at its university rate of $100/night. (Undergraduates are not accepted into Todai’s guest houses.) Todai will also arrange, when possible, summer internships in corporate labs in Japan for Princeton students. Both universities have procedures in place for providing ID cards, laboratory, intranet and library access. We plan to rely on these procedures with the fewest modifications possible.

Faculty: 3 each way per year. Typical visits will be few days to a week due to time constraints. Housing will be similar to that of grad students (the Forest Hongo hotel is also excellent, as several of us from Princeton can attest).

2. Joint Workshop

By the middle of Year 2 (AY 2014-15) over dozen exchanges on multiple levels will have occurred, at least one course will have been taught, and multiple joint projects will be in progress. This will be the time for cementing our relationship, and for beginning to plan beyond the three-year horizon of the present proposal. We will organize a joint workshop with three
goals: (i) tell the entire collaboration what we have been doing; (ii) brainstorm for ideas to deepen our partnership and expand our collaboration; and (iii) pull the students, both undergraduate and graduate, into open and uninhibited discussions.

For scoping the size of the workshop we assume that it will be organized in Princeton, that all faculty partners (8 from Todai and 8 from Princeton) and 8 students from each side will participate, for a total of 32 participants. We assume that 2 faculty participants from Tokyo will be in the US for other scientific conferences (saving travel costs), and will arrange to have 4 students from Tokyo working at Princeton at the time. The workshop will run for a week, beginning with arrival on a Sunday and departure on the following Friday.

3. Teaching Program

We plan to jointly teach both graduate and undergraduate classes. They will be separately listed for credit at both Princeton and Todai, and students at will enroll at their home institution for credit. The tricky problem is scheduling.

Teaching schedules at Princeton University and the University of Tokyo

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The teaching terms at Princeton are 12 weeks long, with typically 3 to 4 hours of lectures for a total of 36 to 48 classroom hours, plus 1 hour of precept. Fall term courses are taught from mid-September to mid-December; 1-½ weeks of study period and 1-½ weeks of exam period follow in January. Spring term courses run from the beginning of February to the end of April, and are followed by 1-½ weeks of study period and 1-½ weeks of exam period in May. Exceptionally, teaching may continue into the study periods. A one-week long break divides each teaching term into 6-week long parts.

The teaching terms at Todai are for undergraduates 13 weeks long with 1-½ hours of lectures per week plus two weeks for exams, for a total of 21 classroom hours. For graduate students, 15 weeks of lectures with 1-½ hours of lectures per week. Terms are April 1 to July 31, and October 1 to January 31. Graduate courses may be taught outside of standard teaching term.

These schedules suggest that undergraduate courses would be taught jointly best during the fall, and graduate courses during the spring, as the two following examples show.

Proposed Course Scheduling

Undergraduate course to be taught in the fall of AY 2014-15:

The fall term schedules of Todai and Princeton overlap sufficiently to allow teaching a nearly complete undergraduate course on the standard Princeton schedule. The period from October 1, 2014, (beginning of Todai’s term) to January 13, 2015 (end of Princeton’s study period) comprises
10-1/2 weeks that can be used for teaching at Princeton. Therefore a course taught for 3 classroom hours a week on the Princeton schedule from Sep.10 – Dec.12, 2014 (36 hours) would overlap for 27 classroom lecture hours with Todai’s schedule.

Graduate course to be taught in the spring of AY 2013-14:

Todai’s capacity to teach graduate courses during breaks will allow us to fit a graduate course into the teaching schedule of Princeton’s spring term, and provides some flexibility in scheduling. For example, we could the graduate course with Todai’s standard length of 14 lectures of 1-½ hours each over 7 weeks of 2 lectures each. This course could start on the Monday, March 24, following Princeton’s spring break, and run into the first week, ending on Friday May 9, of the study period.

Specific course plans

Graduate/advanced undergraduate class: Spring of 2013 (and 2014 or 2015)

In the spring of 2014 we plan to teach a graduate course on Large Area Electronics. Prof. Someya already did participate in a similar course at Princeton in the spring of AY2009-10. This course is a good example for the course we want to co-teach first.

AY09-10 course description: Large-area electronics is a new frontier at which dense and localized electronic devices, made of conventional as well as revolutionary materials, are spread out over large surfaces. Conventional electronics compares to large-area electronics like the human brain does to the body's nervous system, which is composed of extremely diverse sensors and actuators; the two can work synergistically towards systems with new possibilities. Presented research will range from architectures and application demonstrations to circuits, new materials, devices and processes.

AY09-10 teachers: Profs. Craig Arnold (MAE), Branko Glisic (CEE), Antoine Kahn (ELE), Lynn Loo (CHE), James Sturm (ELE), Naveen Verma (ELE). Princeton Global Scholar Prof. Takao Someya of the University of Tokyo (March 23, 25, 30 and April 1), Dr. Kunigunde H. Cherenack (ETH Zurich), Prof. Barclay Morrison (Columbia University), Dr. Stéphanie P. Lacour (University of Cambridge), and Prof. Siegfried Bauer (University of Linz).

The new course will be co-taught by the fourteen faculty participants, seven from the University of Tokyo and seven from Princeton. The course will have the length of a standard course at Todai, i.e., 14 lectures of 1-1/2 hours each. The course will be simulcast to Tokyo and Princeton. We are considering recording the lectures.

We plan to teach first this graduate course for three reasons. One, its subject is of strong mutual scholarly interest so that the teachers can prepare their material at short notice. Two, the graduate course can be taught in the mixed Todai-Princeton schedule and format explained above. Three, a graduate course has a shorter approval cycle than an undergraduate course.

We may co-teach a graduate course in similar format during the spring of 2015, depending on the progress of preparing a jointly taught freshman course (see below).

Teaching hours will be 7pm (EST) or 8pm (EDT) at Princeton and 9am at Tokyo. The course will be simulcast to both sites, and may be taped.

Depending on which year we teach the undergraduate course, we may offer the graduate course again in 2014 or 2015 (whichever year has no undergrad course).

Freshman Engineering Course: Fall of 2014 or Fall 2015.
We are planning to teach an introductory freshman engineering course. Todai teaches such courses in the freshman year to enable students to choose a major during their sophomore year. Princeton teaches EGR 191 and EGR 192, An Integrated Introduction to Engineering, Mathematics, and Physics, and also EGR 102A, Engineering in the Modern World (see http://commons.princeton.edu/kellercenter/courses/emp.html). While Princeton’s Integrated Introduction courses emphasize fundamentals, its Engineering in the Modern World course and Todai’s freshman courses emphasize systems integration and social infrastructure. This suggests that a co-taught freshman course will stretch the minds of students on both sides.

This course will take some time to prepare. One reason is that the development of a coordinated freshman course will take time. Teaching it fully in English will place an additional burden on the Todai faculty. A second reason for taking time is that, at both Princeton and Tokyo, general engineering courses for undergraduates must be vetted by the departments, the engineering school, and at the university level. Therefore preparing this undergraduate course will take use to at least the fall of 2014 and more likely of 2015.

Note: The Department of Materials Science of Todai and MIT are co-teaching freshman and sophomores, with 11 “events” between April 11 and May, including three team meetings on Saturdays: https://gpep.mit.edu/. Briefly, the schedule is Apr. 11 (Thu) Self-introduction by video recording; Apr. 18 (Thu) Team formation and Lecture #1; Apr. 20 (Sat) 8-10am JST [Apr. 19 (Fri) 7-9pm EDT] International Skype meeting with MIT; Apr. 25 (Thu) Team discussion #1; May 2 (Thu) Lecture #2; May 9 (Thu) Lecture #3; May 16 (Thu) Team discussion #2; May 18 (Sat) 1-4pm, Team discussion #3; May 23 (Thu) Pre-presentation; May 25 (Sat) 10am-5pm JST: Todai-MIT International Student Symposium; May 30 (Thu) Wrapup. The schedule suggests that the course is more an exercise in teaming than academic instruction. This interactive program was organized following the initial experience that online lectures were not attractive to undergraduate students.

Course technology

Todai is fully equipped for distance teaching. At Princeton the plan is to make use of room Wallace 001 in the Wallace Social Science building, which is the videoconference room located nearest to the Engineering Quadrangle. This room also is fully equipped for simulcasting.

5. Intellectual Rationale:

As stated above, we are seeking to build a permanent collaborative program on what we call broadly “large-area electronics.” This is a new field of research with many potential applications, often in human-machine interactions such as electronic skin, medical electronics, and paper-like displays. Tokyo and Princeton are leaders now, individually. The collaboration between eight faculty on each side will ensure a dominant research position world-wide and well into the future.

In this section we outline briefly the individual strengths of each side and the fields of mutual collaboration. The actual projects and resulting exchanges will occur organically by individual faculty interaction as research and opportunities evolve.
Participating faculty groups at Princeton and Todai, the technical strengths of each institution, areas of joint collaboration, and the linkages.

5.A. Strengths of Princeton

Large-area low-power systems (Verma, Sturm, Wagner, Glisic, Adriaenssens).

A multi-faculty program at Princeton is creating new architectures for large-area electronic (LAE) systems. Thin-film circuits are fabricated over large surface areas for integration with advanced nanoscale complementary metal-oxide-silicon (CMOS) integrated circuits (ICs). The application functionalities of these systems are deployed in the LAE domain. The present focus is sensor arrays for structural health monitoring.
Thin-film transistor technology and physics
(Wagner, Sturm, Loo, Kahn)
Princeton has a complete design and fabrication process for thin-film transistor circuits on plastic substrates. This competence originates in basic studies of materials and device physics.

Surface and interface science; organic and permeation barrier films (Kahn, Loo, Wagner)
Understanding the atomic, molecular, and electronic structure of interfaces has been a research focus at Princeton for many years. Inorganic/metal, inorganic/organic, organic/organic interfaces have been studied, with eventual application to devices. Preparation and evaluation of organic films and of barrier films with ultra-low permeability are coupled with interface studies.

Organic and hybrid organic-silicon heterojunctions and solar cells (Sturm, Kahn, Loo, Rand).
Heterojunction devices translate fundamental understanding of interfaces to applications. Controlling the orientation of organic molecules raises solar cell efficiency, as do selectively carrier-blocking barriers applied to silicon.

5.B. Strengths of Todai

Ultra-thin / flexible substrates (Someya, Takeya).
Ultrathin, lightweight, large-area organic photovoltaic cells and thin-film transistors are fabricated on 1 micrometer-thick polymeric films. Since the base film is extraordinarily thin and fragile, special care is taken in substrate handling and sophisticated manufacturing processes are needed. A novel room temperature process is compatible with ultrathin substrate films, resulting in the world’s lightest and thinnest organic devices. Transport properties of high-performance organic thin-film devices are studied.
**Organic TFTs and circuits** (Sakurai, Takamiya)

Novel circuit designs overcome limitations of organic devices with low carrier mobility. They include physically cut-and-paste circuit layouts for robotic skins and ultralow noise organic amplifiers for sheet-type electromyographs. One focus is hybrid systems of high-performance silicon LSI and large-area organics.

**Encapsulation for medical applications** (Sekitani, Sekino)

Biomedical and health-monitoring applications make full use of the mechanical durability of organic flexible devices. New encapsulation films of ultra-thin, ultra-flexible organic-inorganic hybrid materials protect organic implants from humidity.

**Animal in-vivo experiments** (Abe, Isoyama)

Abe and Isoyama are experts on artificial heart devices and hold the record for the longest lifetime of fully implanted artificial hearts. They combine engineering with medicine to introduce flexible implantable electronic devices, such as flexible sensors for accurate control of artificial hearts. Their long-term goal is to vary the rate of blood circulation as people’s physical activity changes while walking, running, or sleeping.

**5.C. Areas of Joint Collaboration**

A major strength of the proposed initiative is that it brings together researchers whose strengths jointly form a continuum spanning from materials to systems. The joint projects emphasize this continuum towards synergistic outcomes that will seed future programs, which will be holistic in nature and thus most likely to translate into societal impact. A brief description of the proposed projects follows in a bottom-up order.

**Stability science**

While flexible and large form factor is transformational from the perspective of sensing...
functions, one of the most critical challenges facing the underlying devices is that the associated processing causes substantially-elevated device sensitivity to environmental and operational conditions as compared to conventional electronics. Innovations in materials and processing are required to ensure device stability for realizing high-value applications. By focusing on fundamental understanding at the materials and processing levels, previous research at Princeton has made substantial strides in this area. We aim to establish a joint program to apply this approach broadly to materials systems and devices.

**Self-assembled monolayers**

Conventional electronics has benefitted from tremendous scaling trends (known as Moore’s Law) that have led to staggering capability and energy-efficiency improvements in transistors. This has been the primary driver for the range of new applications we have seen over the past three decades. This project aims to apply a similar principle to thin-film-transistor technologies by enabling aggressive processing methods based on self assembly of critical device layers. Most notably, aggressive processing of the gate dielectric, which determines the effectiveness of a transistor’s control electrode, will enable low-power and high-sensitivity devices to enable ubiquitous electronics in mobile and embedded applications. Previous research at Tokyo has led to thin-film transistors that have enabled circuits operating at supply voltages among the lowest reported to date (<2V). We aim to apply this breakthrough broadly to thin-film circuits.

**Energy harvesting**

As electronics become increasingly embedded, powering them has emerged as one of the most critical challenges. Thanks to the wide range of transducers that can be formed using thin-film processing methods, a wide range of energy-harvesting devices become available. On top of this, the attribute of flexible form factor, enables unique opportunities for interacting with ambient power sources, and the attribute of large area enables physically-large devices that are able to harvest substantial power. These factors position thin-film electronics as a highly-compelling technology for energy harvesting. This project investigates new transducer devices for energy harvesting as well as the integrated circuitry required to efficiently extract the harvested energy and process it into usable forms for practical systems. Our previous research has demonstrated great promise in both these areas. The figures below (Tokyo) shows an energy-harvesting system integrated into shoes to extract power from human walking, and (Princeton) an energy-

![Footstep-energy-harvesting system within the sole of a shoe.](image)

![2V organic-transistor circuits](image)

![Solar-harvesting sheet with embedded power conversion for wireless device charging.](image)
harvesting system that uses a flexible solar-cell sheet with embedded power converters to wirelessly charge mobile devices placed nearby. We aim to build a common platform of energy harvesting technologies that can be applied to any autonomous large-area and flexible system.

**Low-power interfaces to biology**

![Image of a highly-flexible array for surface electromyography for future prosthetic applications.](image1)

Flexible electrode array for physiology recording during tissue trauma.

Electronics has begun to demonstrate tremendous value in clinical applications, enabling unprecedented capabilities for therapeutic and prosthetic functions. As electronics systems become increasingly valuable these application, the critical challenge that is emerging is the ability to extensively interface systems with biological tissue despite mechanical mismatches that give rise to patient discomfort, histological responses, and/or poor signal transduction. Flexible electronics provides unique opportunities to address mechanical mismatch; however, use in medical applications raises new challenges related to device encapsulation, implantation/surgical protocols, extreme flexibility, etc. Our previous research has demonstrated devices that provide a starting point for researching these challenges in the context of medical applications. The figures above show (Tokyo) an ultra-thin high-density electromyography recording array for prosthetic-control systems, and (Princeton) a highly-flexible electrode array for assays studying the impact of trauma on tissue in the central nervous system. In this very-long term research our aim is a continuous exchange of techniques for reducing electric power consumption and mechanical irritation by medical implants and at electronic/biological tissue interfaces.

**Large-area flexible sensing systems**

A transformational aspect introduced by large-area electronics is the ability to create very large-scale interfaces to the physical world. The value that this brings is illustrated in an ongoing project where we focus on monitoring the structural health of critical civil infrastructure, such as bridges. This application requires strain sensing on a centimeter scale yet over large portions of the structure to effectively detect indicators of early-stage damage. The figure below shows (Tokyo) the form factor for the sensor arrays we are researching, wherein sensors with a pitch of a few millimeters are fabricated into arrays spanning square meters. Looking beyond the sensor arrays, this project recognizes that the realization of systems to address applications requires embedded functionality for instrumentation, computation, communication, and power management. This project investigates system architectures that leverage high-performance CMOS integrated circuits, which currently are the workhorse technology for the microelectronics
New sensing devices integrated into a dense and expansive form factor for large-scale sensing. Integrated systems combining large-scale sensing with instrumentation, computation, power management, and communication. Industry, alongside large-area electronics to realize complete systems. The second figure (Princeton) shows a preliminary system that integrates thin-film strain sensors with subsystems for sensor control, instrumentation, power harvesting, and communication. These large-area systems will be at the core of our collaboration. Princeton and Tokyo are world leaders in this emerging field. We have complementary strengths in the constituent technologies, and aim for a joint program that will extend our lead.