The IEEC: Combining Research, Education and Economic Development

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I. Introduction: History of the IEEC

The Integrated Electronics Engineering Center (IEEC) was founded by local industry several years before the IEEC became an NSF-sponsored State Industry University Cooperative Research Center (S/IUCRC) in 1991. The three founding companies (or their descendent organizations) are still sponsors of the IEEC. These companies are Universal Instruments Corporation, General Electric Aerospace (now Lockheed Martin Control Systems), and IBM Federal Systems (now Lockheed Martin Federal Systems). Digital Equipment Corporation joined the IEEC in 1992 and subsequently resigned when their business declined. Later General Electric Corporate Research and Development Center joined as a submember under Lockheed Martin Control Systems' sponsorship. IBM Microelectronics joined in 1994 and the Matco Electronics Group joined the IEEC in 1996.

Its founding by industry still has a profound effect upon the center: relationships are intimate. Members have a long-range commitment to the success of the center. While the industrial sponsors have made it clear that they hope to directly benefit from the center's research, they would like the entire local packaging industry to benefit, especially in the Susquehanna Valley, but also throughout New York State and the region. All industrial sponsors have spent considerable energy in advising the IEEC.

The IEEC has benefited from two different levels of advice from industry. As with all S/IUCRCs, the IEEC has an Industrial Advisory Board (IAB). The IEEC's IAB is composed of senior executives of its sponsors (president, chief engineer, site manager, etc.) These senior advisors have proved very useful in direct advice and help on specific projects.

The IAB also silently performs another function. The members provide the time of senior technical personnel to work with the IEEC as members of the Technical Advisory Board (TAB). TAB members are typically senior technical managers who are still intimately acquainted with the technology. Over the years, their advice has been extremely valuable. Not only have they offered purely technical advice, but often insightful programmatic advice: Would the risks of a proposed research project be reduced if Task A were performed after Task B? Most faculty have come to respect and value comments from the TAB on their research plans and progress.

The IEEC has enlisted about 45 Associate Members, most of which are small New York companies. Associate members are not required to pay fees except when specific special tasks are to be performed by the IEEC that would not be useful to other companies.

The IEEC maintains a proactive relationship with many small companies. It has been a pleasant surprise to discover that often small companies can and will help one another. Since they are almost always too busy keeping themselves out of trouble, an independent party, such as the IEEC, can draw attention to opportunities - if we keep in touch.

The New York State Science and Technology Foundation (NYSSTF) designated the IEEC a New York State Center for Advanced Technology (CAT) in 1993. The NYSSTF is the same state agency that provides matching state funds to the NSF's contributions as an S/IUCRC. The responsibilities of a New York CAT are similar to those of an S/IUCRC: perform state-of-the-art research for economic benefit in collaboration with industry. The center is not divided into an S/IUCRC part and a CAT part. We work as a unit, although the NSF S/IUCRC program and the NYSSTF CAT program have different reporting requirements.

In the past year, NYSSTF has required CATs to report their impact on economic development in more precise ways. The IEEC applauds this effort, because it forces the center to be more careful in planning technology transfer. The most significant new requirement on CATs is to track the effect they have had on economic development. It is possible to more easily track the Center's impact on small- and intermediate-sized companies than large companies. This will be discussed below. For this reason, the Center has begun to devote a slightly larger portion of it resources to these smaller companies.

II. Goals

The primary goal of the IEEC is to produce leading-edge electronics packaging research and transfer the results of this research to local, state, regional and US industry. The Center demands only excellent research and uses industrial advice and other peer review techniques to confirm the value of the work.

A related goal is to enhance the economic growth of New York State and the United States. We hope to aid the

US in recapturing more of the electronics manufacturing business it has lost overseas. Manufacturing can provide jobs for more than engineers and scientists.

The IEEC aims to educate its students so that they can easily and rapidly become significant contributors to the New York and US electronics industry, especially in manufacturing, an area that has been somewhat neglected by US academic institutions and students over the past several decades.

The center will experiment with different methods of technology transfer and then evaluate their effectiveness with respect to the size of the industrial receptor and its business niche.

The center also has a goal to develop novel educational opportunities in cooperation with its faculty and the Office of the Dean of the Watson School of Engineering and Applied Science. New opportunities include a "Certificate in Packaging" for MS engineering graduates, graduate courses offered within individual departments that make use of state-of-the-art IEEC research, two different distance learning offerings, and many professional and continuing educational opportunities.

III. Accomplishments and Productivity

A. Education

1. Certificate in Electronics Packaging

The Watson School plans to offer a "Certificate in Packaging" to students who graduate with master degrees in Electrical, Industrial, and Mechanical Engineering. The student is required to pursue thesis or project research related to packaging and to take two of the three graduate courses in packaging offered by the Electrical, Industrial, and Mechanical Engineering Departments, as well as a one-hour credit seminar course supervised by the IEEC.

There are problems in running an interdisciplinary collection of courses. For example, should an electrical engineering course omit advanced topics in signal integrity because mechanical or industrial engineers are not well acquainted with Maxwell's equations? During the past year, the course instructors have made plans to alleviate the worst of these problems by including brief reviews that might benefit a student who is majoring in a field, as well as bringing a non-expert up to speed.

There is another possible approach to this problem. Recently the IEEC has discussed with Professor Peter Krusius of Cornell University the possibility of both universities cooperating to produce a series of video modules on specific topics. Thus, for example, an instructor in the mechanical engineering packaging course could refer a student to a video module on finite element analysis and be sure that an electrical or industrial engineering major would have sufficient background to understand the mechanical engineering course.

All of the graduate packaging courses were offered last year on EngiNet, the SUNY engineering remote learning facility. This permits any engineer in the state (or out of the state) to work towards a masters degree by taking video courses. Many of the students are engineering majors at other SUNY campuses that do not offer specialized courses in packaging. These courses are available nationally and internationally.

2. Seminar in Packaging

The one-hour credit seminar course mentioned above is a Watson School course, not a departmental course. This course offers an overview of packaging, with speakers from industry and faculty from Binghamton and other universities. This was originally developed at the suggestion of Professor John Fillo, then the chairman of the Mechanical Engineering Department. Fillo was concerned that graduate students could pursue research in one aspect of packaging, but not understand the broad aspects of packaging. The course has proven to be popular, sometimes many faculty will attend a particularly interesting lecture. Some students who have graduated have told us that the vocabulary that they picked up from the seminar was useful to them in job interviews. The IEEC took charge of organizing this course because of its intimate acquaintance with industry experts.

3. Graduate Electrical Engineering course in Electronics Packaging

The Electrical Engineering Department's course in electronic packaging has been strongly influenced by IEEC research. The emphasis on research in electronics packaging has influenced several courses that are taught by Watson School faculty who are engaged in packaging research, but the research has impacted a graduate electrical engineering course in packaging to the greatest extent. This course is offered at least every other year on EngiNet.

The purposes of this course are to:

a) Describe those aspects of electrical engineering that are important for electronics packaging,

b) Acquaint the graduate electrical engineering student with other fields that are important for electronics packaging (thermal and mechanical engineering, metallurgy, manufacturing, materials science, and industrial engineering),

c) Expose the student to current research in electronics packaging and guide the student in reading current technical literature, and

d) Show how economic considerations and evolution of markets for electronic systems have changed the emphasis in current research.

Slightly more than half of the course concerns the electrical engineering aspects of packaging. This covers a review of the basics of transmission lines and a brief discussion of superconducting transmission lines. Superconducting lines provide an alternative look at the basics rather than a practical and useful example of interconnections. Cross talk is studied in detail. CMOS circuits used as drivers and receivers in modern computer systems are described. Signal integrity and the low frequency treatment of "delta-I" noise are carefully discussed.

The first use of faculty research in the course is the introduction of high frequency aspects of signal integrity using software developed by Professor Jiayuan Fang's group. They have developed a software package that permits viewing the evolution of animated voltage waves that are introduced between metal layers in packages or circuit boards by currents through vias. The voltage waves are solutions to the full 3-D Maxwell's equations, so accurate simulations are obtained.

One demonstration for the class was the use of decoupling capacitors to reduce unwanted voltage excursions and "ground bounce". It is easy to play "what if" games by placing one or a few capacitors at various places in the simulation. New solutions are obtained in a few seconds. While the students in the course do not manipulate the software, they can gain physical insight in how to obtain minimum noise or ground-bounce by optimally placing the capacitors.

We have found that this demonstration is easier to accomplish if the students can visit Fang's laboratory. Only prerecorded videos are convenient to use for remote learning, and the demonstrations therefore have less spontaneity. Professor Fang has established a company, Sigrity, Inc., to commercialize the software. Similar animated simulations, but with less detail, can be viewed at Sigrity's website (http://www.sigrity.com/).

The course topics that do not involve electrical engineering make heavy use of lab demonstrations and current research. Measurements of thermal resistance and thermal contact resistance served as a part of the introduction to thermal management issues in packaging. The electrical engineering students fully appreciated that measurement of thermal resistance was more difficult than the measurement of electrical resistance only after they had seen the thermal resistance apparatus in Professor D. C. Sun's laboratory.

The opto-mechanics laboratory, established by Professor Mani Prakash and now supervised by Professor James Pitarresi, served as an introduction to the problems of thermal strain in modern packages. Moiré and Twyman-Green interferometry illustrated the in-plane and out-of-plane strain in ball grid array (BGA) packages. BGA packages mounted on laminate substrates show the greatest strain, and are therefore the subject of the most thorough finite element modeling, which was also demonstrated to students in the class.

Solder is the basic glue for electronics packaging assembly. After a detailed introduction to phase diagrams, the students concentrated their attention on study of tin-lead system. In some years, Professor Linda Head's students arranged for a demonstration of stencil printing of solder pastes.

Professor Timothy Singler and his students have illustrated the hydrodynamics and the physiochemical hydrodynamics of solder flow and wetting in laboratory demonstrations and lectures to the class. The behavior of molten solder is governed by hydrodynamics, surface tension, wetting attraction, and gravity. Professor Singler has elegant videos of solder bridging and de-bridging. Singler has studied the effect of solder volume, surface tension, density, and shape and separation of metal lands on the instability of momentarily formed bridges. Capillary instabilities can guarantee the breaking of solder bridges. These studies combine basic science and valuable practical knowledge for manufacturing.

One of Singler's PhD students, Stephan Meschter, has lectured on and demonstrated to the electrical engineering students the basics of solder wetting and how he is attempting to establish the first standard for solder wetting that is based on firm scientific principles.

The complexity of manufacturing considerations is important for electrical engineers to appreciate, even if they do become manufacturing engineers when they take jobs in industry. Presentations by Professor K. Srihari greatly help with this appreciation. Srihari has presented a lecture on an overview of the packaging assembly process, stressing all the manifold considerations that go into choosing solder paste, flux, reflow temperatures and atmospheres, and clean-up.

An important adjunct to the main topic of this lecture is an introduction to expert systems. Expert systems are sometimes used to guide the choices of parameters for manufacturing engineers. Many electrical engineering students who are highly skilled in computer programming have not previously heard of expert systems. The important consequence of this lecture is that the students are assigned a problem: choose an acceptable combination of solder pastes, solder fluxes, and cleaning procedures based upon various sets of boundary conditions (high reliability, industrial, or commercial applications, and manufacturing environments,).

I believe that the students benefit most from an appreciation that manufacturing engineers must function in a complex world and solve difficult problems. They thereby gain respect for engineers in other fields. The introduction of current research from other fields also helps the student to gain respect for those fields. This respect is important when the student enters industry. Here he will be judged on "how good an engineer" he is, not just on "how good an electrical (or mechanical or whatever) engineer he is". Electronics packaging is an unusually interdisciplinary area. He or she must learn to work with other disciplines.

4. Other Contributions of the Center to Education

The Watson School continues to offer annual Symposia on Packaging and Solders, and the IEEC continues to co-sponsor them. They have begun to draw an international audience in recent years. Besides advising the Office of Continuing Education by setting the program and inviting speakers, the IEEC has encouraged smaller New York companies to attend by supporting the registration costs. Without this encouragement, some small companies would not be able to afford to send personnel to any scientific or technical meeting. Several small companies have greatly appreciated this.

IEEC researchers and member companies have participated in an NSF-sponsored project to produce instructional videos on "Manufacturing Experts in the Classroom." Video recordings of actual assembly and fabrication procedures permit demonstration of modern manufacturing operations to a far wider audience than that which could actually visit a factory.

B. Research Results

While many examples exist of the significance of IEEC research projects, we choose to concentrate attention here on three projects that have clearly impressed the scientific community and have also vitally influenced industry.

Professor Jiayuan Fang of the Electrical Engineering Department has examined the critical obstacle to the design of future electronics systems: the difficulty imposed by higher clock frequencies and shorter time-duration pulses. When any logic gate switches, it draws more current than it does in its quiescent state. Not only will this extra current disturb voltage and ground supplies, but the power supply current surge will always couple to some extent (sometimes to a large extent) to the signal system. It is desirable to minimize fluctuations of the power supply as well as the coupling between the power system and the signal system to preserve signal integrity. But as clock rates on chips become faster and pulses have shorter duration, the preservation of signal integrity becomes more challenging. Furthermore, the wider buses in modern chips require more gates to switch simultaneously, thereby increasing the total current switching disturbs. The extra current, delta-I, required by switching gates results in excess noise, commonly called "delta-I noise."

A fundamental insight that is exploited by Fang is that the full solution to Maxwell's wave equations in typical packaging structures can be obtained by decomposing the three-dimensional solution into two kinds of waves: waves that propagate in two dimensions (radial waves) and waves that propagate along strip lines or microstrip lines. The result is that this software is 1,000 to 10,000 times faster than alternative methods and more accurate. It has been installed at several facilities of members of the IEEC. It can calculate the voltage wave forms as a function of time between tens of conducting planes in a few seconds under the influence of hundreds of simultaneous switching events.

Molten solder is a fluid and its equilibrium shape is determined by the combined effects of the forces of surface tension, gravity, and the physiochemical interactions (wetting) between the solder and the surfaces it touches. Under the reasonable assumption that equilibrium configuration of the solder will determine whether bridging will occur, an important computational tool that can be applied to this problem has been introduced by Brakke with his *Surface Evolver* program. Professor Timothy Singler, together with colleagues Zhang and Brakke, has explored the theory and computationally determined shapes of molten solder. Singler concludes that the final shape of the molten fluid solder is very close to the final shape of the solidified solder, so long as solidification does not take place too rapidly. Therefore, the final solid shape for the solder filet can be predicted. Besides the computational work, Singler has performed laboratory experiments which elegantly confirm the predictions of theory.

The shape of solder bumps that are used in BGA and flip chip technology can also be predicted using *Evolver* . Two important results can be derived from this. First, the forces that tend to cause alignment of chip to board can be calculated. (The forces that arise from surface tension are useful in correcting minor misalignments in assembly.) Second, the shape predictions can be incorporated into a standard finite element mechanical code (such as Ansys) to analyze the strength of solder joints (after they have solidified). Optimal shapes for the greatest strength have been analyzed by Professors Pitarresi and Singler. Subtleties have been uncovered theoretically, and experimentally confirmed.

Several new packaging structures require an "underfill" material that is "underflowed" between the package and board (in a BGA) or under a chip that is mounted directly to a board (in "flip chip" mounting). Underfill has gained greatly increased importance since technologists have dared to flip chip mount a chip directly onto an organic board, because of the great mismatch in thermal coefficient of expansion between a silicon chip and polymers. (A significantly lesser problem occurs when a silicon chip is mounted on a ceramic carrier where there is much less mismatch in the coefficients of thermal expansion.)

The purpose of the underfill material is to reduce the strain on the solder balls and thereby prevent premature failure of the mounting. The underfill material is often an epoxy with suspended particles, usually composed of silica.

The combination enables a closer match to the CTE of the solder balls. The most common method of applying the underfill is to permit capillary action to cause the flow of the material under the chip or package. Forcing the flow could cause damage to the solder joints. The flow of this composite material is non-Newtonian and, except for trivial aspects, its behavior is a major theoretical problem.

Directed but basic research to understand the underfill process has been conducted by an interdisciplinary team consisting of Professor Eric Cotts of the Physics Department and Professors Gary Lehmann and Timothy Singler of the Mechanical Engineering Department. They have investigated both theoretically and experimentally several aspects of the underflow process and have shown that hydrodynamics by itself can cause the formation of undesirable voids.

The work of Cotts, Lehmann and Singler is extremely closely monitored by IEEC sponsor companies. One, in fact, attempted to sign them to an exclusive contract. This is impressive because all they were doing was very basic fluid flow studies - but in a practical application arena. Their work has also been recognized by a major DARPA contract. DARPA's requirement to widely disperse their results throughout US industry was one reason they did not accept an exclusive contract from an IEEC sponsor.

C. Influence of Industry on Research Projects

Some people assume that because the center is closely advised by industry that it must support mainly short-range research projects. This is not the case. While industry advisors insist that the research be relevant to their needs, they purposefully desire longer- ranged research projects than their companies usually support.

This assertion is supported by a catalogue of the major research projects supported by the IEEC in the 1997-1998 academic year. Of course, the year-to-year goals will change to some degree for multi-year projects.

Title	Faculty	Number of Years Supported
Computational Electrodynamics	Fang	7
Opto-mechanics	Prakash; then Pitarresi	7
Solder Physics	Singler	6 1/2
Intermetallic Formation	Clum and Cotts	5
Dendritic Connections	Constable and Sun	4
Underflow Physics	Cotts, Lehmann and Singler	4
Conductive Polymers for In-board Resistors	Jones	2 1/2
High Thermal Conductance Interface Materials	Lehmann	new (7/97)
In-process Control of Plating Baths	Sadik	new (9/97)
Solder Fatigue Basics	Pitarresi	new (9/97)
Resistance Spectroscopy Applied to Thermal Cycling	Constable and Pitarresi	1996 - 1997; renewed 3/98
Area Array Cost Estimation	Santos	new (9/97)

The above summary shows there are seven projects that have been supported for more than two years. Six have been supported for four or more years. At least two, and probably more, of the new projects will be supported for a second year. One of these new projects is almost a sure bet for a third year of funding, unless something unexpected goes awry. This is hardly a record of supporting only short-term projects.

D. Technology Transfer

The IEEC makes use of all conventional methods of technology transfer: written reports, talks, formal and informal meetings both at the university and at industrial labs. Occasionally we also make use of video or CD-ROM media. However, we believe other methods of technology transfer are more effective because they involve people moving from one setting to another.

Perhaps the most successful and most used method of technology transfer has been exploited by Universal Instruments and, to a lesser extent, by the Matco Group and Dovatron. Every year 20-25 MS candidates in the System Science and Industrial Engineering Department pursue part of their thesis work at Universal Instruments' Surface Mount Technology Laboratory. There are occasional PhD candidates that also follow this route.

Technology transfer occurs automatically when research is carried out in a sponsor's laboratory. Universal employees work directly with students so the results are transmitted on a person-to-person basis. Universal employees can witness the experiments while they are being performed. Besides the direct person-to-person transfer, conventional reports, both written and oral, are delivered. Some of the oral reports are quite formal and are presented to Universal's customers. This is an extremely direct method of positively influencing economic outcomes of research.

Perhaps the ultimate benefit for students who have worked at Universal is jobs. They are eagerly sought after by Universal's customers and by members of their industrial research consortia. Mr. George Westby, Manager of the Surface Mount Technology Laboratory, told me that at dinner, after a day's presentations to members of Universal consortium, only one student had a single job offer; all the others had at least three, and one student had seven. But beyond the job offers, the faculty has heard that these students have done very well in industry.

The center believes that the best technology transfer is person to person. There are several examples over the years. Currently two such transfers are underway. One is because of the wisdom of Lockheed Martin Control Systems (LMCS), formerly General Electric Aerospace. Over the years, LMCS has about 25 employees who have obtained MS degrees at the Watson School, studying under professors who perform research in packaging. The equipment and even the knowledge of these faculty were enhanced by their participation in the IEEC. But LMCS has gone further. They have supported Stephan Meschter as a full time PhD student under the direction of Professor Timothy Singler. Clearly Meschter will bring back to LMCS rather intimate knowledge about solder wetting, the subject of his thesis.

Another current example of person-to-person technology transfer is the participation of Mr. Steven Gonya of Lockheed Martin Federal Systems (formerly IBM Federal Systems) in an IEEC research project. Gonya has been working in the Opto-mechanics Laboratory in cooperation with Professor Mani Prakash one or two days a week in a program to predict the reliability of ceramic ball grid array devices by using both finite element analysis and optical measurement of strain. As this program has progressed and more specific studies have become useful to LMFS, Gonya has been given some space and specialized equipment to rapidly conduct tests without interrupting the main research effort. Gonya's direct participation in the research and testing assures that this information is directly transferred to industry.

E. Contribution to Economic Development

The IEEC has discovered that it usually requires different kinds of effort to bring economic benefit to different sized companies. We have also learned that different sized companies may require different effort in order to track the effect on a company's business. Tracking the effect of our economic development activities is required by New York State.

The smallest companies usually have no need for advanced research, but they can often be greatly helped with information that is commonly known among research faculty and engineers at large corporations.

The effect on employment is minor if one doubles the employees in a two-person company. On the other hand, a 10% increase in employment in a 500-person company can be significant in a local area. It is, however, usually extremely difficult to track the effect of center research on a large company.

Fortunately, it is sometimes possible to judge the effect of research. This is the case with Universal Instruments, a large company by common definition (1,200 employees). It is a company that has a relatively narrow focus and is extremely efficient in making use of university research. Last year, Mr. Gerhard Meese, president of Universal Instruments, stated that over the previous two years Universal had hired an additional 250 people. Of these, he estimated "about 25-40 were the direct result of the University."

The IEEC has an immediate goal of doing a better job of tracking the impact on economic development we have on all our large member companies.

IV. Future Plans

The IEEC has begun implementing a plan to establish a fabrication/assembly facility in the engineering building. About $600K of equipment has been ordered and installed in the past year. Some of this has been provided by an NSF award two years ago. This equipment includes a stencil printing machine, a dispenser for solder paste or epoxy, a furnace and a flip chip bonder. Analytical equipment purchased includes x-ray inspection equipment, especially useful for inspecting BGAs and flip chip attachments and a rheometer.

Future planned purchases include several optical microscopes, a digital camera for optical microscopes, a scanning electron microscope, and a furnace for curing organic materials. Funding sources for most of this equipment have been identified. A wide range of analytical equipment already in operation in various laboratories of individual faculty will also support this equipment. A manager for this facility has recently been hired.

This assembly facility will have multiple uses. It will permit a wider range of assembly research than faculty can practice at industrial laboratories. It will also permit undergraduate students to participate in assembly and fabrication research. We also anticipate that small companies will find the fabrication facility invaluable in experimenting with new processes. Often these small companies find it difficult to interrupt an on-going process even for the potential advantage of defining a new process that could potentially bring the company new business. Many of these small companies wish they were competent in some modern assembly processes such as BGAs (ball grid arrays) that will undoubtedly become more important in the future. Access to an experimental facility such as we have planned will permit them to educate themselves rapidly at minimal cost. Finally, there are indications that even large companies such as IBM might make use of such a facility from time to time, because of the difficulty in interrupting manufacturing operations at a large company.

The fabrication facility is expected to be in full operation by the third quarter of this calendar year. We anticipate that it will greatly benefit our educational, research, and economic development missions.