Building Collaborative Teams
For
Multi-Disciplinary Educational Projects in Optoelectronics

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ABSTRACT

Multidisciplinary team-oriented research is an effective method for investigating systems spanning multiple knowledge areas. Building on cross-functional team strategies developed for highly competitive industries, experts from a variety of technical domains can be brought together in a team and focused toward a common set of goals. However, building and maintaining these teams is an art that combines technical, social, and management skills, and requires proactive, conscious attention to enable and achieve positive results. This paper explores some avenues toward effective multi-disciplinary team building, and explores the educational potential associated with team-oriented research. The first step in team research is to identify an appropriate technical topic and to build a team around the technical areas associated with that topic. Consensus building is a key aspect to successful team research, as is the goal that every team member achieves research sub-goals as part of the larger effort. Team researchers optimally have a willingness to act in a cooperative rather than competitive fashion with team members, initially communicate with minimal jargon, meet regularly with other team members, share resources, and be personally responsible for their portions of the project. Additional strategies include recognizing and appreciating myriad levels of diversity in the group, valuing the cross disciplinary education of team members, inserting new technology when appropriately mature, and setting timelines and resource allocation using a consensus approach. Multi-disciplinary teams can address problems which are higher in complexity than those addressed by individuals, yet also offer the leveraging, and time and funding buffering that is so important in shortening research time cycles.

1. INTRODUCTION: ADVANTAGES OF TEAM RESEARCH

There are many advantages to multi-disciplinary team research. The rising complexity of systems naturally leads to projects which cross multiple disciplines. The reality of human existence is that each individual is time limited. As such, one individual can absorb only a finite amount of information in a given time period. Realistically, most people have broad, shallow knowledge, and are highly trained experts with depth in only a narrow range of topics. For example, in the field of integrated optoelectronics, there are few individuals (if any) who have in-depth education and experience in optoelectronic interface circuits, devices, and integration. Thus, a team of researchers, one or more experts in each of these areas, and beyond these areas, for system applications, can address research topics in this area much more effectively than a single individual. This multi-disciplinary approach can be used to create and educate teams, which are much more competitive technically than a single investigator.

A second advantage to team research which is developed over a long term and over many projects is the leverage and buffering effect that the teams can produce. For example, if an individual is a member of two separate teams on two different, but synergistic projects, then funding lapses or time pressures on one project can be buffered by the other projects. A truly successful team researcher, who might play a role in multiple teams, with multiple agendas, can significantly leverage resources, and offer better results to each team. In this way, the efforts of the team can total to more than the efforts of the sum of the same individual researchers, or, in technical terms, $2+2 > 4$.

Another interesting aspect of multi-disciplinary research is that many important discoveries occur at the boundaries of two fields. These boundaries are most fruitful when they are at an early stage of exploration, in most cases, where students

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have not yet been trained in the overlap area. If multiple experts in the two areas can communicate, ideas can be generated in this fertile area faster than they can be explored. This is truly exciting science, and can invigorate teams with a mandate for exploration. This is teamwork at its best: creative, expansive, encompassing, and enjoyable on the most basic level of human existence – what some have called "flow". The productivity enhancements of empowered teams has not been lost on industry, and has been credited as a breakthrough for increased productivity in the 1990s [1]. To educate our students, both at the graduate and undergraduate level, in multi-disciplinary teamwork is a service both to the students themselves and to the industries that will employ them.

2. IDENTIFICATION OF THE RESEARCH TOPIC AND TEAM MEMBERS

Research topics and team members for multi-disciplinary team research must be carefully chosen. Either can be the initial starting point, but before embarking on a program, often the team and the topic must be honed. If a research questions or topic initializes the process, then the team members can be chosen on the basis of their technical expertise and on their interest and willingness to work as part of a team. One effective method of creative idea generation is to gather a group of experts and focus them on a particular question or topic, and conduct a brainstorming session. An effective brainstorming session approach is for the individuals to generate ideas without any criticism of the ideas generated. After the brainstorming, then the ideas created can be culled down through critical analysis and consensus to arrive at a team focus. It is not uncommon for ideas from one researcher to prompt ideas from another, and, in this way, produce a multiplicative landslide of creativity. Alternatively, a multi-disciplinary group of researchers can agree to meet to brainstorm – to discuss creative ideas, which might evolve into research projects by simply exploring and discussing the boundaries of their fields, using the same brainstorming techniques mentioned above.

Identifying and building the multi-disciplinary team is critical to the success of the project. When initializing teams, it is important to discuss with each individual their goals and expectations from the project. There are stipulations, which team members should agree to, in order to positively contribute to the team, and these should be identified at the outset, and are discussed below. When formulating a team, both short and long term views are valuable. Many teams last for one project; the most effective last many years, over many projects, and long lasting bonds are formed between the team members. Even though many persons might believe or wish themselves to be successful team players, not all are, or can be educated to be. If an individual is interested in being educated in team dynamics, it is appropriate to attempt this, but it is not wise to attempt to force behavioral changes on those who resist. Egos, particularly inflated egos, can be destructive to teams. As a famous, herein unnamed researcher was recently quoted as saying, "Team players don't get famous," however, levels of effectiveness and competitiveness as a team must be weighed against individual ego gratification. Clearly, each individual needs to make that personal decision. Just let dysfunctional teams dissipate after a project is complete (one way or another).

Two complementary, and critical aspects of team success are to have a common team goal, yet to ensure that each individual researcher realizes some individual goal, such as a publication, in their own field. For example, in our projects, we attempt to identify multiple papers focusing on different aspects of joint system, each which can be published without substantial duplication in a journal corresponding to the different areas of expertise represented by the researchers. If any team member is relegated to service work, without intellectual content, trouble will ensue as the project takes on less importance to that team member than other projects with more intellectual or reward prospects. It is critical, however, that all of the team members arrive at a consensus definition of the primary goals of the overall team project. Individual projects must serve the overall goal, and have a defined time plan for the translation of maturing technologies into the primary project. To reach consensus on the primary project is to ensure that all of the team members are "rowing in the same direction" to meet a common goal which may temporarily subsume other, more individual goals. This is key to the success of the team project.

The acceptance of individual responsibility is another key aspect of team research, as well as a valuable skill for students to learn. In multi-disciplinary team projects, usually the responsibility for an area rests on a very few persons. A matrix structure to the organization of groups and teams can be an effective tool for encouraging and enhancing individual responsibility. For example, in our multitude of integrated optoelectronics projects, Professor Jokerst and one to two graduate students in her group are solely responsible for the optoelectronic devices and integration on each project. Thus, each student takes responsibility for the optoelectronic integration portion of their project, for example, at the weekly project meetings. These students do not feel isolated in their optoelectronic integration work, however, since, at weekly meetings of Professor Jokerst's group, all of the students on the myriad projects meet to discuss each project so that the synergy of the projects can be explored, and the students can aid each other with questions and problems. This matrix approach, illustrated in Figure 1, is an effective organizational tool for productive multi-disciplinary teams.

Project \ Expertise	MBE Materials Growth	Integrated Optoelectronics	Analog Circuits	Digital Computational Systems
Compliant Substrate Materials Growth	Brown Student Shen	Jokerst Student Shen		
Transceiver Links	Brown Student Dagnall	Jokerst Students Vrazel, Thomas Undergrad Team	Brooke Students Chang, Young Laskar Student Bergman	
Smart Camera (imager with on-focal plane processing		Jokerst Students Vendier, Bond	Brooke Students Park, Joo	Wills Student Kee Shik
Alignment Tolerant Optoelectronic Packaging		Jokerst Students Vrazel, Geddes Undergrad Team	Brooke Students Carastro, Park Laskar Student Chen	Wills Student Taha

Figure 1. Matrix organizational chart for multi-disciplinary teams.

Subteams within teams is another effective cross-training tool for educational knowledge transfer, and for developing leadership skills within the group. For example, advanced and new graduate students are often paired on a project, to ensure that, up departure, the knowledge of the advanced student remains in the group, and the less experienced student is trained in the process. In addition, the advanced student's communication skills are sharpened by the necessity of knowledge transfer, and, optimally, mentoring occurs, to the benefit of the learning experience of both students, as well. Organizational subteams can also teach leadership and management skills. Subteams consisting of students from multiple groups can each be focused on different aspects of research. For example, in the Optoelectronic Packaging project shown in Figure 1, there were three subteams of students. All students were responsible for all aspects of the project, however, there was a managerial leader for each subproject. The three subprojects were modeling, experiments, and experimental testbed automation. All of the students performed work in all three areas, often as a group, but there was one leader of each subproject responsible for assuring and reporting weekly progress in that subarea. This approach teaches time management, leadership, and organizational skills.

We seek diversity in teams from a variety of viewpoints. Certainly, for multi-disciplinary teams, a diversity of technical backgrounds is highly important. In addition, we seek cultural, racial, and gender diversity to draw in multiple viewpoints and to educate all team members to appreciate the contributions of all individuals on the project. This is a particularly important skill to learn since the workforce is increasingly diverse. Leadership roles and success will increasingly depend upon building consensus and effective management of diversity. We also seek educational level diversity in that undergraduates, graduates, post doctoral associates, and faculty are involved in research projects. Too often, the sizable contributions that undergraduate teams can make to a project are underestimated by faculty. In addition, treating the graduate students at a collegial level, appreciating that they have knowledge and ideas that are valuable empowers students toward high achievement. Above all, effective and efficient utilization of human intellectual resources is paramount in team research.

1. TEAM INTERACTION APPROACHES

An effective team must be proactively nurtured to succeed. There are some simple guidelines, which can be used to nurture and enable team members so that they have a positive experience and desire and are enabled to contribute to the work. Perhaps the most important intangible factor in team research is a level of dedication to the team work that can weather both positive and negative results. At times it is more difficult in a team environment to admit error or unintentional omission, since that admission is made to a larger audience than oneself, and perhaps, a student (as is often the case in individual work). However, there is truth to the adage that "Joy is Multiplied and Sorrow is Divided Among Friends," and the same can be true for team research. Everyone will make mistakes and hit obstacles. After all, coming to a negative conclusion, while not particularly satisfying, still yields valuable information. Part of the essence of engineering is to work around obstacles. Teams can be damaged, and sometimes irreparably destroyed by fingerpointing and assignation of blame when something goes wrong. Recognizing a mistake, without implying intention, negligence, or inadequacy, but simply stating technical fact, is the first step. Then quickly move on to the positive aspect of focusing the team on the best solution to the problem. Everyone on the team will make mistakes – no one is immune (even faculty!). There is no sense in damaging an effective team due to what is most probably a transitory blip that can be solved by the team. In a truly effective team, members work together positively to solve difficulties, and thus, the "sorrow" is lessened considerably. This behavior is learned, and not everyone is adept at learning this behavior.

In most organizational structures, there is necessarily a hierarchy of responsibility. Ultimately, there must be one person responsible for assuring that the work is progressing. This individual must also be dedicated to nurturing the intangibles associated with team interactions. Those senior team members with the salary and hire/fire authority must be dedicated to the formation and maintenance of the team as a group. This group is a university is usually the faculty. There are points at which team personal dynamics, time constraints, and technical challenges will put pressure on the team. Team leaders must be willing to say to students who are in the learning phase of team involvement, "Yes, it will be worth it, keep going!" Industry does this very well – in many industrial team situations, an individual's job retention is based upon their successfully involvement in their work team.

Recognition of diversity, and ensuring that every team member is rewarded for success is an important part of team management. An optimized team consists of complementary technical and administrative skills, with education toward skill building in all facets of the work. These skills include organizational skills, such as setting up meeting times and space, financial planning and execution skills, including purchasing and accounting, communication skills, such as presenting work to technically diverse team colleagues, or leading a technical discussion in the group, management skills, such as resource allocation, and social skills, such as nurturing a positive group dynamic. All of these skills are important to a successful team, and should be sought after when considering team members. However, those individuals that are skilled in one area and weak in another should be educated in weak areas, and help to educate in their strong areas. Team-oriented research is not simply focused on research results and on the technical education of the team members, but also in teaching team members how to be exemplary colleagues and effective team members.

There are preferred interaction methods for teams. First, everyone individual on the team has an important role to play. In a properly formulated team, strictly "service" sectors should be minimized, since there should be intellectual content and reward for everyone. Given this, the different technical groups should be educated in their co-importance. Often, a subgroup may consider their work to be of more importance, or more vital to the project than another subgroup. This is not usually the case, as all elements are needed to perform the work. Why would unnecessary elements be included in the first place? Most often, these problems arise due to lack of education regarding the technical role that each subgroup plays in the project. This is understandable; in large projects, there may be little technical overlap between two diverse groups. Education of the entire team on the role and importance of each subgroup is a critically important effort.

Jargon is one of the prime dividers in the formation and development of multi-disciplinary teams. Individuals who cannot communicate effectively with each other often become frustrated, and just stop speaking entirely. A successful communication approach for multi-disciplinary collaboration is to use no jargon beyond that of a Scientific American level. It may take quite a bit longer to describe ideas than if jargon were used, but the communication is much more effective. As time passes and the team is exposed to the work and intellectual output (e.g. papers) of each subgroup, limited use of jargon will occur. But do not be surprised that concepts basic to one subgroup (undergraduate level) will be new, and need often repeating to another subgroup. Needless to say, a great deal of time and patience will be invested in the collaboration. However, the payoffs can be stupendous.

In addition to jargon, communication style can enable or hinder collaborative efforts. An often observed scientific method of communication, which is aggressive and confrontational, is not optimal for team-based work. This approach begets distrust, nervousness, and paranoia among the team members, and, while it may work in the short term, team members in the long term will not desire to be a part of the team. Team building through positive reinforcement – praise – is a highly effective tool if used honestly. Positive, careful wording to even the seemingly smallest memo or message, whether verbal, written, or electronic, is very important. Above all, respect for all team members and their diverse talents must be reflected in every communication. Collaborative, cooperative discussions where constructive criticism is offered, and it is clear that everyone in the room is focused on moving ahead in a positive fashion, empowers individuals to perform far beyond their initial expectations. It is the individual fulfillment of group expectation: if an individual knows that the team believes that they are capable of a task, then they are filled with the confidence to address that task.

One of the most important tasks that the team leadership engages in will be consensus building. Consensus building begins at project initiation, continues through the team building phase, and never ends. Decision by consensus is far superior to leader mandate. Decision by consensus often leads to better decisions because more intellectual input is involved, and by the mere inclusion of that intellectual input, there is an unspoken message of respect that each team member receives. This co-decision making process is educational, as well, since the team's members hear the diverse inputs of all of the team members. It is much more likely that the united team will move forward based upon the decision convinced, since they were the originators, that this is the best decision. Thus, consensus decision making may take more time than mandates, but the decisions produced are better, are more likely to be embraced by the entire team, and the process serves to nurture the positive team interactions.

4. ORGANIZATION OF THE MULTI-DISCIPLINARY RESEARCH EFFORT

In many multi-disciplinary research efforts, there is a span of technologies, which can range from system-level to device or material level. This can result in particularly strong system research, since the system architecture and the materials and device characteristics can be used to design for trade-offs that produce a system whose architecture is enabled by the devices and materials, as well as driving new device and material designs for specific system needs. For example, optical interconnection can be used to create three dimensional (3D) interconnected silicon systems, and the system architectures and topologies implemented in the research can be uniquely enabled by the new 3D interconnection options.

When designing a multi-disciplinary research program that utilizes research from a wide range of technologies on the "food chain," ranging from materials and devices to circuits to systems, it is vital to realize that research breakthroughs will optimally occur in all technical subcategories represented in the research, however, not all of these technical advances can be incorporated into a full system simultaneously. Thus, it is of utmost importance that subsets of the technologies studied be demonstrated individually within the context of the limitations of the integrated system, and then, as the technologies mature, they can be integrated into the full system. For example, a new emitter structure should be designed and tested within the drive current, efficiency, and power dissipation limits set for that device by the system, but it should be tested on pads before it is integrated onto a driver circuit. Likewise, the emitter integrated onto the analog driver circuit should be tested as an individual transmitter before the transmitter is integrated into a mixed signal system with digital and analog circuitry mixed with optoelectronics. Once a transmitter has been designed, integrated, and tested to operate, even if it does not initially meet speed and power dissipation specifications, then the systems researchers can design architectures that demonstrate the fundamentals of the multi-disciplinary research effort with the interfaces that are available. Then, as faster or more efficient or lower power dissipation transmitters are developed, they can be fairly seamlessly inserted into the next design cycle of the system. Thus, new technologies evolve through a range of implementations, from basic breakthroughs in a subgroup to prototyping between two subgroups, to, in a system project, full prototype implementation involving all of the multi-disciplinary groups.

Given this introduction of technology as it matures for all technical subgroups working on the project, it is important in the project planning phase not to cause any subgroup's work to rely on the results of any other subgroup. For example, in designing the transmitters discussed above, optoelectronic materials that are research topics should not be the sole source of material for the integrated transmitters. This will cause too much delay in the implementation of the optoelectronic devices and integrated transmitters. Thus, one should either have in hand material which will meet the device needs in a non-optimized fashion at the onset of the project, or budget in the project for one round of purchased material so that the material growers have time to work on their materials research effort. Likewise, the transmitter circuits should be designed so that they can be electrically tested without optoelectronic device integration. Thus, the transmitters can be tested before integration while the optoelectronic devices are being tested.

Careful planning, where the research efforts of one subgroup are not dependent upon delivery of research results from another group, as well as minimizing research downtime for any subgroup (design the system so that everyone always has relevant research to perform), is an essential aspect of successful multi-disciplinary collaborative research. This planning may take significant energy at the outset of the project, but is well rewarded by reduced angst and improved efficiency. In particular, programs that span long portions of the "food chain," or range from materials and devices to systems, require careful planning. One pitfall is that of maintaining interest. For example, a system researcher may design an architecture and integrated circuit based upon projected optoelectronic link specifications. However, that link may not be realized until the much later in the project. Thus, interim goals and related, yet branching systems research must be identified so that the most extreme (the highest (e.g. systems architecture) and the lowest (e.g. materials and devices)) subgroups remain engaged in the process while the research moves toward full integration of all subgroups.

To aid in the realization of multi-disciplinary project planning, weekly meetings of the multi-disciplinary groups (shown as the horizontal rows in Figure 1) are the most effective method of realizing results. These weekly meetings are most effectively devoted to updates on the current work of each subgroup and any looming issues, discussion of the goals for the next week, as well as of longer term goals, and finally, a short presentation each week, by one of the subgroups, on their work and it's importance to the project. This final topic is simply educational, and arguably has the most positive long term effect of the meeting time spent. Multi projects with the same groups can be grouped into weekly meetings, and, there is a significant time investment involved, however, once again, the payoffs can be tremendous. Often, it is also helpful for two technical subgroups to meet, and these meetings should be in addition to the regular meetings of each technical group, as indicated in the vertical columns in Figure 1.

Timeline planning, resource allocation, and design of experiments (DOE) are additional tools that are vital to multi-disciplinary team research. PERT and GANTT charts aid in the time and resource allocations for projects. In particular, resource and time planning can identify critical dependency paths, to which more attention can be focused. DOE methods enable researchers to optimize the information obtained from a set of experiments by identifying actual and potential interdependencies among variables, and designing a series of experiments to identify and decouple interacting factors so as to identify the most critical variables in a process.

5. MULTI-DISCIPLINARY PROJECT CASE STUDIES

In the last ten years at the Georgia Institute of Technology, the faculty authors and their students have been involved in many multi-disciplinary optoelectronics programs, involving subgroups of the authors. Herein, we will examine a few of these projects as case studies for multi-disciplinary collaborative team research and education in optoelectronics.

5.1. Integrated Optoelectronic Receivers

Integrated optoelectronic receivers are a simple example of optoelectronic detector device experts performing collaborative research with analog circuit designers. Few, if any, individuals are trained to the extent that they can perform competitive research both in optoelectronic devices and integration as well an in analog integrated circuit design. Thus, this is an appropriate project for multi-disciplinary collaboration. This research topic is also a good stepping stone to rich research areas such as optoelectronic links for communications systems, broadband optoelectronic networking interfaces, three dimensional computational structures using vertical optical links, interconnection in electronic systems, and smart photonics. The team initially consisted of an optoelectronic device and integration subgroup coupled with an analog circuit subgroup. As time advanced and new devices dictated new materials, an optoelectronic materials growth subgroup was approached and brought in, and, as the link speeds increased, an RF design subgroup was added.

The historical sequence of events started with the demonstration of compound semiconductor detectors bonded to host substrates such as silicon (Si), as shown in the photomicrograph in Figure 2. In parallel, Si CMOS VLSI receiver circuits were designed and fabricated at the MOSIS foundry[2]. After both the optoelectronic devices and the circuits were successfully independently fabricated and tested, then they were integrated together in a receiver circuit, as shown in the photomicrograph in Figure 3. The first version ran at 80 Mbps, the second at 155 Mbps, and the third at 250 Mbps[3]. A 622 Mbps and 1-2 Gbps series of receivers using Si CMOS VLSI are now in test. Each of the ensuing receiver implementations incorporated either new device designs (including the alignment tolerant inverted metal-semiconductor-metal (I-MSM) photodetector[4], with fingers on the bottom of the thin film device for higher responsivity than conventional MSMs) or new circuit designs (single ended to differential receivers for mixed signal noise immunity) or new circuit fabrication technologies (from 2 to 1.2 to 0.8 to 0.5 to 0.35 μm CMOS). Comparators for digital input/output were separately tested and then implemented into the link, as was an analog biasing scheme using digital programming signals (the BiasBus) to reduce the pincount. Access to GaAs electronic circuits through Triquint enabled the RF subgroup to design an optoelectronic interface circuit which, when integrated with the same photodetectors, operated at 2.4 Gbps[5], as shown in Figure 4. A 10 Gbps link using InP/InGaAs detectors and a GaAs traveling wave amplifier circuit has been designed and integrated, and is currently under test. This work was then used to pursue other, more system oriented multi-disciplinary projects.

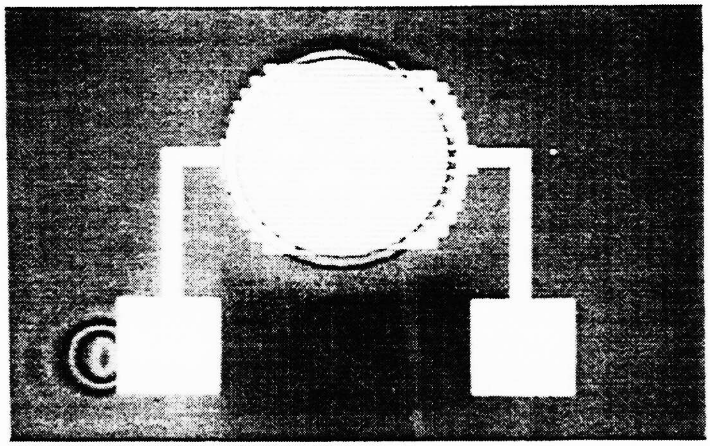


Figure 2. Thin film metal-semiconductor-metal GaAs/AlGaAs photodetector integrated onto a Si host substrate.

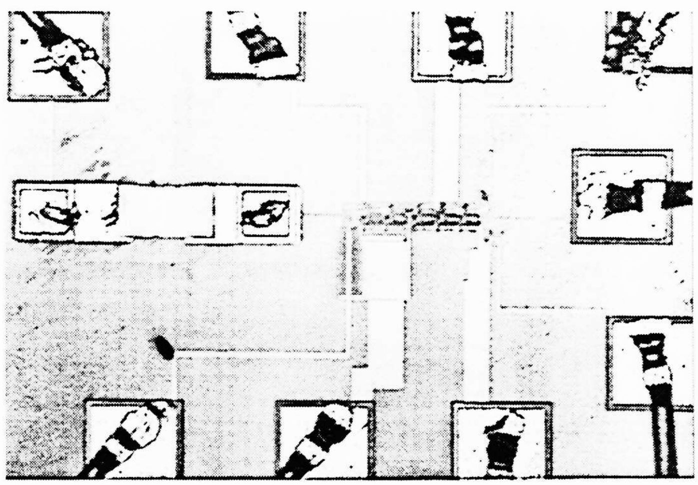


Figure 3. Si CMOS receiver integrated with an InP/InGaAs thin film inverted MSM (I-MSM).

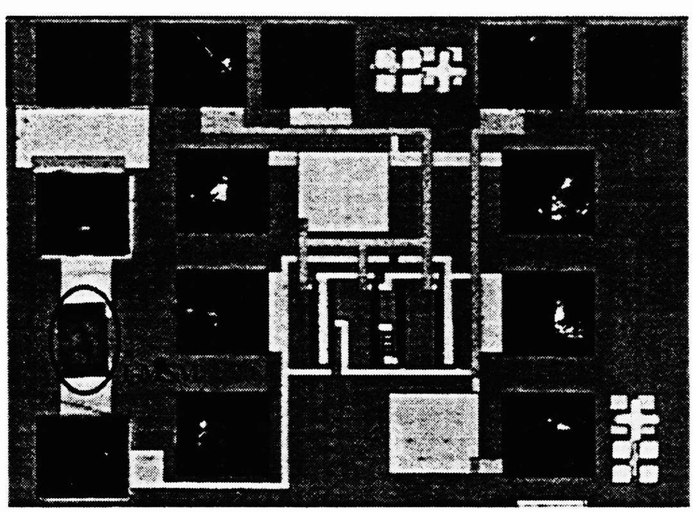


Figure 4. GaAs receiver integrated with an InP/InGaAs thin film I-MSM.

5.2. Low Cost Fiber Interconnections for Automotive/Avionic, Remote Video, and In-Home Fiber Backbone Applications

Integrated optoelectronic receivers can be used in some simple systems that are well served through the introduction of optical links. Low cost optoelectronic fiber optic and high density wiring (HDW, or multi-chip module) substrates offer new realms of application for optical interconnection. For the Ford Motor Company, a fiber optic wiring harness replacement has been designed, for the Georgia Tech Broadband Consortium of companies, an in-home fiber backbone has been designed, and for the National Science Foundation Electronic Packaging Research Center at Georgia Tech, a remote video system using fiber optic links is under design. All of these systems use integrated transceivers, and all contain some system design which is implemented either in Si CMOS or in an electrical interconnection HDW substrate.

The automotive/avionic fiber optic wiring harness replacement was a collaborative effort between optoelectronic materials, devices, and integration with Si CMOS analog and digital circuit designers. The goal was a low cost, alignment tolerant system using large core plastic optical fiber, an array of Si CMOS BJT detectors which were slow but exhibited high gain (30 A/W responsivity), a thin film optical emitter bonded directly into the center of the Si CMOS circuit (for a single fiber bi-directional link), analog Si CMOS interface electronics, and digital Si CMOS control electronics, as shown in the fully integrated photomicrograph shown in Figure 5[6].

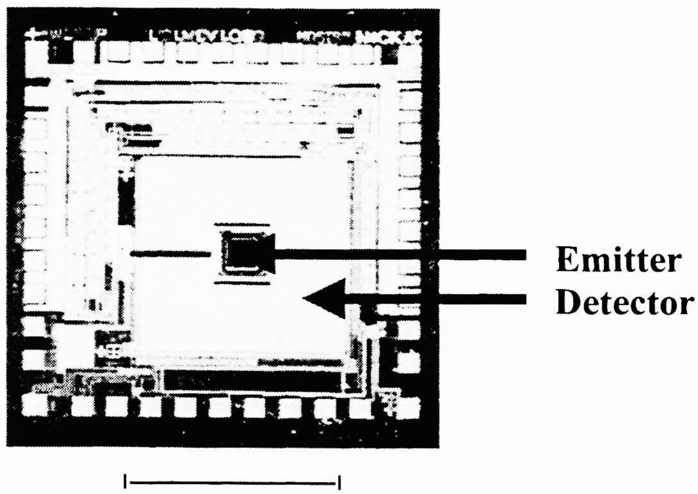


Figure 5. Thin film GaAs emitter and CMOS BJT detector co-located on a Si CMOS circuit with analog interface circuits and digital control circuitry.

This project was designed, fabricated, and tested by a multi-disciplinary group of researchers who included a materials growth, optoelectronic device and integration, analog circuit, digital circuit, and optical alignment tolerance modeling researchers. The first circuits were electrically tested, and then integrated with a thin film light emitting diode that had already been integrated and tested on pads. Subsequent improvements included more complex digital control and interfacing circuitry, higher speed analog interface circuits, and red light emitting diodes for lower propagation loss in plastic optical fiber. Models were developed to describe the alignment tolerance of two of these integrated optoelectronic subsystems connected by a large core diameter optical fiber. These models were validated by experiment, and are now being used to project the performance of alignment tolerant optoelectronic links at higher speeds[7].

5.3. The Smart Camera

For advanced imaging applications, including high frame rate imagers and portable lightweight imagers with on-board signal compression for remote operation, the utilization of optoelectronic interconnect mixed with smart pixel technology and digital signal processing on-chip can produce exciting multi-disciplinary collaborative projects. This "smart camera" series of projects utilized the expertise of optoelectronic materials, device and integration researchers, and analog and digital circuit, and parallel computational architecture researchers.

Figure 6 is a photomicrograph of an imaging array that was developed as a first step toward the integrated smart camera system[8]. This integrated optoelectronic device array was bonded directly on top of the Si CMOS circuits, with each detector pixel connected directly to the circuitry underneath it. However, the amount of Si area under each pixel is small, and will decrease with decreasing pixel size, so there is not much room for signal processing under each pixel.

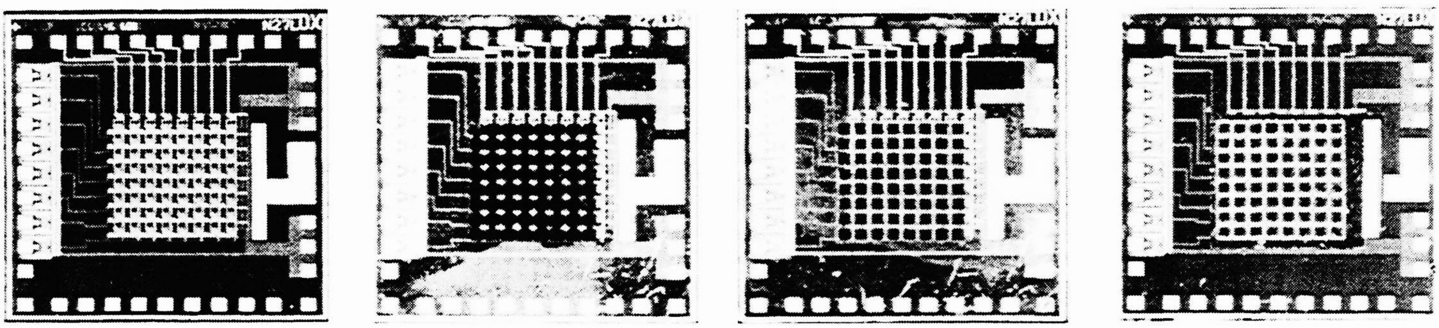
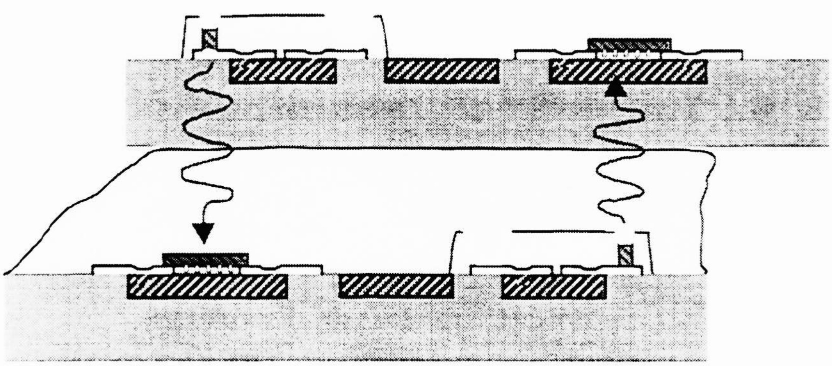


Figure 6. Integration sequence for thin film GaAs detectors bonded directly on top of Si CMOS circuits.

The problem of limited signal processing under each pixel is a problem that can be solved using a 3D vertical optical through-Si interconnection to a second layer of Si CMOS processing. This type of 3D optical interconnection is also one possible solution to the projected (2007) crisis in interconnection density in the current SIA roadmap. By using 3D vertical optical interconnections, as illustrated in Figure 7, interconnection between layers of signal processing can be achieved using optical wavelengths to which Si is transparent [[9]]. A number of these 3D optoelectronic links have been reported. Figure 7 shows an eye diagram for one link of a three layer 3D Si CMOS circuit stack, which had 10^{-9} BER at 1 Mbps on both vertical optical interconnection channels.[10]



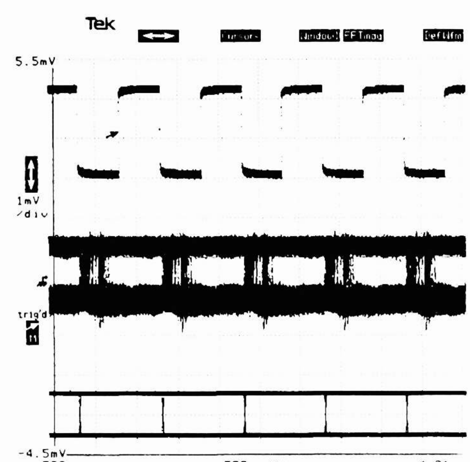


Figure 7. Schematic of 3D through-Si optical interconnection links, and eye diagram for one link of a three layer 3D Si CMOS circuit stack, which had 10^{-9} BER at 1 Mbps on both vertical optical interconnection channels.

This type of 3D vertical optical interconnection released massively parallel processing architectures from a 2D chip to chip interconnection scheme[11], and enabled architectural topologies that had not been reported. In this fashion, the implementation of a new type of optoelectronic link, a through-Si vertical optical link, directly enabled a new massively parallel Si computational architecture, PICA[12]. This 3D vertical optical interconnection scheme was then used to implement the smart camera concept[13]. Namely, a two layer Si CMOS imager was designed, in which the first layer was a Si CMOS imager with one sigma delta analog to digital converter per pixel[14], and these signals were then multiplexed onto an on-chip optical transmitter which transmitted the signal through the Si CMOS circuit to another Si CMOS circuit that had an integrated detector with a differential receiver circuit and a microprocessor, the SIMPil processor, on the bottom chip. Figure 8 is a photomicrograph of this set of chips.

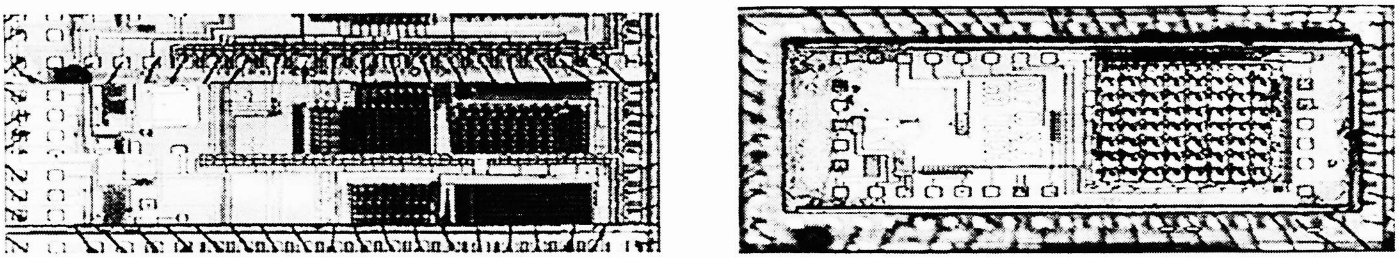


Figure 8. SIMPil microprocessor, differential receiver, and I-MSM on bottom chip (left), and, stacked on top of the bottom chip, is the imaging array with a transmitter and λ = 1.3 μm emitter emitting down, through the Si CMOS chip, to the detector on the bottom chip.

6. CONCLUSIONS

Multi-disciplinary team research has many advantages, including accessing a group of experts who can each bring their individual knowledge to bear on a problem, provide leverage and buffering effect for funding lapses or time pressures, and, in terms of technical effectiveness and output, can total to more than the efforts of the sum of the same individual researchers. Many important discoveries occur at the boundaries of two fields. These boundaries can produce bountiful results if multi-disciplinary teams whose members are familiar with the overlapping fields can conduct collaborative research. Teamwork can lead to productivity enhancements, and to enhanced education for our students, both at the graduate and undergraduate level. Project, personnel, interaction, and organizational strategies for multi-disciplinary team research are effective, and, when applied to nurture teams, can produce not only outstanding technical results, but also personal bonds that last forever among colleagues, and an exciting, creative work environment.

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