US Army Research Office

Electronics Division

2001 Strategy Plan

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SECTION I - INTRODUCTION

In the 21st century the U.S. military will face a wide range of challenges that will require it to find peaceful solutions to global conflicts, as well as, to fight and win wars. Dominance must be maintained that deters miscalculations by adversaries through means of overwhelming superiority in all areas of combat. Dominance is gained through the quality of weapons, technology, tactics, leadership, and national will. The *Army Vision* statement (http://www.army.mil/armyvision/armyvis.-htm) lists seven objectives of the modern army that are crucial for fulfilling its world leadership responsibilities. They are: Survivability, Sustainability, Agility, Lethality, Responsiveness, Versatility, and Deployability. These objectives must be maintained with greatly reduced numbers, which can only be achieved with technological superiority. For this reason, electronics is widely recognized as a key force multiplier, underpinning the Future Combat System, as well as the Objective Force. Advances in electronic technology have played decisive roles in contemporary successful military engagements, as in Desert Storm. However, in this age of information and weapons proliferation, the ambitious goal of keeping one step ahead of the adversary dictates continued advancement in electronic disciplines. Thus, substantial research must be performed to acquire the necessary knowledge that will enable us to field new systems and update current systems for the Army in the 21st century.

The Electronics Program consists of a combination of needs and opportunity driven research. In some cases the needs-driven research projects originate with a highly directed search effort, for example the broad agency announcement for innovative landmine detection proposals. In other cases the projects arise from the discovery of a unique opportunity that fits a known need. The pure opportunity research areas tend not to be driven by specifically recognized Army needs. Some can have an immediate indirect impact on Army systems, such as new techniques that enhance and speed up EM computer modeling. Others can result in future systems requirements once the unforeseen technical capability has been demonstrated and analyzed, for example the new opportunity area in cellular electronics.

Typically, major breakthroughs in electronic systems occur at the fundamental physics and device level. These breakthroughs are usually due to higher quality materials, improved device processing, new device structures, more accurate modeling and characterization, or greater device integration. Major advances in electronic device performance propagate quickly through existing subsystems and systems, enabling greater functionality to be realized. Gains at the device and component level lead the way to systems with higher-performance. Examples of device research that have produced revolutionary improvements in systems include: high capacity semiconductor random access memory (RAM) chips for computer memories; low power transistors for wireless communications; and compact optical disks for data storage. All of these advances have had a major impact on both military and commercial systems. At the same time, major improvements at the device level represent input to the system designers and profoundly affect the types of architectures and system structures that are possible.

The main sources of scientific needs are the technology requirements of the Objective Force as listed above. The seven objectives or "ilities" are reinforced by Army capabilities that are supported by electronics research. Table 1 shows explicit military capabilities* and their relation to the seven objectives of the modern army. The military capabilities stress autonomous operations, precise power projection, the ability to avoid or survive hostile threats, and attainment and communication of information throughout the battlespace. The relation between these capabilities and specific electronics research areas will be described in Section III, Research Recommendations and High Priority Thrusts.

Table 1. Army Objectives vs Capabilities	Survivability	Sustainability	Agility	Lethality	Responsiveness	Versatility	Deployability
Low power/high efficiency systems		X	X		X	X	X
RSTA	X		X	X		X	
Chem-bio detection	X					X	
Threat warning	X	X				X	
Communications	X		X	X	X	X	
Information processing	X		X	X	X	X	
Directed energy lasers	X			X			
Sensor protection	X	X				X	
Combat ID/target recognition	X			X			
Smart munitions				X	X	X	
Countermeasures	X	X				X	
Guidance control and navigation			X	X	X	X	X
Highly reliable systems	X	X	X	X	X	X	X
Land mine detection	X	X	X		X		X
Bio-function monitor/control	X	X			X		

It should be recognized that cost is a critical issue for future military systems. The warfighting concepts of the Objective Force demand high technology support, but weapons systems budgets are expected to be historically small. The cost issue is determined by lifecycle costs, in addition to initial acquisition cost, placing an emphasis on supportability and reliability. The criticality of weapons systems cost is an argument for a higher level of technology, not a limitation to relatively low technology systems, although technology should be used only for real payoff capabilities, not for unnecessary complexity. The continuing decline in the cost of personal computing capability is an example of higher technology functionality producing a real overall reduction in capability costs.

*Note: In some cases the military capabilities overlap each other, however, it is felt that this list is appropriate to aptly describe the electronic applications.

Funding strategy for the Electronics Program is determined by the nature of the available funding sources. Core Army Research Office (ARO) program funding is relatively small, but this category provides the most control by the program manager and is the most flexible to exploit new opportunities as they are discovered. If a new project is successful, it is often possible to provide additional funding from sources outside ARO, such as Director, Defense Research and Engineering (DDR&E), Defense Advanced Research Projects Agency (DARPA), or other Department of Defense (DoD) activities. An example is the quasi-optics power combining field, which started as an ARO initiative and is now a Multidisciplinary Research Initiative (MURI) and a major part of a DARPA program. Successful core ARO projects with near term commercial application and the involvement of a small business may be appropriate for Small Business Innovation Research (SBIR) or Small Business Technology Transfer (STTR) funding. So the strategy is to use core ARO funds on the cutting edge projects to establish viability or potential and then to try to leverage these funds with funding from outside sources.

Another strategy issue driven by limited funding for 6.1 research is inter-service cooperation. For example, although the Army has a need for high frequency (HF) communications, the Navy and Air Force use this communications mode to a greater degree and have traditionally had strong research programs in ionospheric propagation physics. For this reason, a deliberate decision has been made not to emphasize this research area in the ARO Electromagnetics Program. On the other hand, until recently, the field of quasi-optical solid state power combining has been primarily an Army-supported research area.

SECTION II - WORKSHOP BACKGROUND

An electronics research strategy workshop was conducted by the Army Research Laboratory's Army Research Office (ARL-ARO) Electronics Division to assess trends in electronics research, to relate anticipated progress to Army needs, to identify areas where research is required to support the Army's future battlefield concepts, and to recommend research priorities. Preparation for this workshop included careful analysis of pertinent planning documents such as the Joint Chief of Staff's *Joint Vision 2020*, the *Army Vision* Statement; TRADOC Pamphlet 525-66, *Operational Capability Requirements*; and Field Manual 100-5, *Operations*. In addition, a careful review of the Army's transformation goals to the Objective Force was undertaken and a workshop speaker was selected that could summarize the Army's goals. Workshop participants were scientists from ARL-ARO, ARL Sensors and Electron Devices Directorate (ARL-SEDD), other Army commands, universities, industry, Defense Advanced Research Projects Agency (DARPA), Ballistic Missile and Defense Organization (BMDO), Oak Ridge National Laboratory (ORNL), and the National Science Foundation (NSF). Many of the participants were also members of the U.S. Army Electronics Coordinating Group, an informal coordination group comprised of Army middle management personnel in electronics. The university and industry scientists were selected carefully, based on their electronics expertise. The agenda, Working Groups lists and their members, and a complete List of Attendees are provided in the Appendix.

The workshop began with plenary sessions to review Army operational doctrine, Army research programs, and the state-of-the-art of relevant science. Colonel William Bransford, Deputy Chief of Staff for Combat Development, U.S. Army Training and Doctrine Command (TRADOC), presented Army modernization and transformation strategy to the workshop attendees. Lieutenant Colonel Brad Tousley of DARPA's Tactical Technology Office presented the Army Future Combat System program. The DoD Strategic Research Areas (SRAs), as well as, Army Strategic Research Objectives (SROs) were presented by ARO's Principal Scientist, Dr. Mike Stroscio. This was followed by presentations describing the state-of-the-art of research in electronics related sciences by experts from DARPA and academia.

After the plenary sessions, workshop participants met in three separate working groups to address electronic research required for the Army of the 21st century and gave special attention to the following domains, which were considered of paramount importance:

1. Electromagnetics
2. Optoelectronics
3. Solid State and High Frequency Electronics

Note that two areas from the 1998 workshop, dealing with Information Science, were not included in this workshop as separate sessions. These were (1) Mobile Wireless Communications and Networks and (2) Image Analysis and Information Fusion. These areas were included as necessary in the other sessions and, also, covered in a separate workshop for the Computing and Information Sciences Division. The working groups in the Electronics workshop identified 22 technical areas where research is required to meet the future Army capabilities. Detailed discussions of the rationales and objectives of recommended research thrusts developed by the working groups are given in Section III.

SECTION III - RESEARCH RECOMMENDATIONS

1 – ELECTROMAGNETICS

Electromagnetics program areas driven by Army needs include antennas, propagation and electromagnetic modeling, advanced, novel circuit integration techniques, and nano-RF components. These areas address the requirements to lighten and reduce the size and cost and logistical requirements of electronic systems. It also opens up larger parts of the EM spectrum, particularly the millimeter wave region, for Army sensor exploitation. Antenna research is aimed at solving problems associated with the extremely ambitious data communications requirements and with improving sensor performance and functionality. The radio propagation research is needed to provide an understanding of and prediction capability for the complicated propagation physics occurring when radio signals travel for long distances over complex natural terrain or urban areas. The specific phenomenology which must be understood to predict data communications channel characteristics are much greater than was required for voice channels in older Army communications systems.

Table 2. **Warfighting Capabilities vs Electromagnetic Thrust**	**Antennas**	**Nano RF**	**RF Circuit Integration**	**Modelling EM & Propagation**
Low power/high efficiency systems	X		X	X
RSTA	X	X	X	X
Chem-bio detection				
Threat warning	X	X		
Communications	X	X	X	X
Information processing			X	
Directed energy lasers				
Sensor protection				
Combat ID/target recognition	X	X	X	X
Smart munitions	X	X	X	X
Countermeasures				
Guidance control and navigation	X	X	X	X
Highly reliable systems	X	X	X	X
Land mine detection	X			X
Bio-function monitor/control				

Table 2 illustrates the major interactions between the research thrusts for the Electromagnetic Program and specific Objective Force and FCS warfighting capabilities.

Research topic areas currently recommended for the Electromagnetics Program follow:

Propagation Modeling

Methods for modeling characteristics of the radio channel for frequencies from HF to the mm wave regime are needed covering the range of open, forested and urban environments anticipated for Army operations. It is anticipated that these computer models will have several applications, including planning for the communication needs in specific Army operations using environmental databases, simulating the performance of new system and network designs, and the determination of optimal conditions for communication. While considerable effort has gone into propagation models that individually account for terrain, vegetation and buildings, models that treats all of these features in a unified framework are called for. New approaches to modeling, such as the use of percolation theory, may make it possible to directly relate statistical channel parameters, such as fading delay spread and angle of arrival spread, to the statistical properties of the terrain, trees or buildings, and to the radio link geometry. Models must be scalable to work with databases covering operational areas that may be 100 km or more in extent, and to integrate databases of individual environmental features. Models should give the frequency response of the channel for ultra-wide bandwidths, as required for simulation of systems such as impulse radio. More accurate representations of reflection/scattering from buildings, and of indoor-outdoor propagation are needed. Measurements in well characterized, full scale or scaled environments are desirable to verify the physical approximations inherent in creating computer models.

Electromagnetic Modeling

The Department of Defense (DoD) is aggressively supporting the development of new technologies, such as microelectromechanical systems (MEMS) and ferroelectrics, and the production of integrated micro-devices for incorporation into platforms, weapons, sensors, and even personnel survivability gear for the war-fighters themselves. The payoff of these new technologies is that they will create new military capabilities and make high-end functionality affordable to low-end military systems. A number of these technologies are based on fabrication techniques used by the semiconductor industry. These processes construct both mechanical and electrical elements with the physical dimensions measured in microns and the number of structural elements on a single device measured in the millions. Many new electronic structures are geometrically complicated, have very different length scales, their performance is governed by coupled physical phenomena (thermal, mechanical and electromagnetic) and are inherently three-dimensional. The solution of coupled multi-scale problems needs to be accurately simulated to correctly predict device performance. New electromagnetic approaches that will provide accurate and computationally efficient solutions to the above problems are sought.

The performance of RF systems is determined by the complex interaction of EM, circuit, thermal, packaging and mechanical effects. System architecture explorations and overall optimum implementation will require comprehensive system modeling that captures fine physical effects. For several years it has been possible to capture entire physical effects for purely digital systems. It is now feasible to contemplate doing the same for mixed signal systems including RF and microwave systems. Modeling the performance of a whole system with accuracy down to the physical level is important in selecting and advancing enabling technologies in the exploration of innovative architectures. Global modeling will support co-design at all levels that will result in a system having better performance than achievable when the individual enabling technologies are optimized to substitute for subsystems (such as filters) realized using existing technologies.

Military tactical communications involve complex environments that include multiple antennas and receive/transmit units and, as a result, require solutions in large computational domains through numerically intensive tasks. Computational techniques which will simulate a wide range of communications problems involving a variety of environments and a number of communication systems are needed. The accurate characterization of co-site interference as a function of a number of parameters that emphasize the physical environment, radio transmission parameters, the type of radiating elements, proximity, communication codes and linearity of the high power/low noise amplifiers included in the system is critical to evaluating the effectiveness of the various communications scenarios. The simulated communications systems may include realistic antenna structures and the RF front-end, either in lumped or distributed form, depending on the phenomenology that needs to be studied.

Antenna Research

Revolutionary and innovative concepts and demonstrations of advanced antenna structures that challenge the fundamental limit imposed on the traditional antennas are needed. Electrically small and/or broadband (not necessarily instantaneously) antenna structures are needed that are particularly important to meet the future army communication, surveillance and EW need. The frequency range of interest is HF through 100 GHz. Many future army tactical operations require multifunction and common aperture antenna architecture. Research on innovative design and hardware implementation for such configurations is needed. Of particular importance for army to be considered is the performance of the antennas operated under the co-site interference necessitated by vehicle (platform) structure unique to army. On the other hand, research is encouraged to make use of the vehicle as a radiating element.

Although the antenna research has a long history, the traditional approach alone may not easily provide increasing important functionality required to the antenna as a part of advanced RF system. A promising recent trend in antenna research is the integrated approach such as active integrated antenna in which active devices are integrated with antenna to enhance the capability of the antenna as well as the RF front end. Such antennas become a nonlinear system and often nonreciprocal. These natures require new characterization, measurement and design techniques not yet exploited fully. Importance of the antenna designed with the packaging or of the self-packaged antenna is growing. In addition, many antennas become essential parts of the multifunction/multi-mission RF-front end by itself or in combination with RF front end or with other backplane analog and digital techniques. Examples of the former include a re-configurable antenna, an antenna that has a self-diplexing function and the one that has a filtering function made possible by microelectromechanical technique.

Space-time coding techniques exploit the presence of multiple transmit/multiple receive antennas to improve performance on multipath radio channels. Such techniques can offer important benefits in tactical wireless communications; such as higher data rates with lower transmit power. Electromagnetic modeling of the multiple antenna environments coupled with the electronic hardware and coding technologies is required to fully exploit this technology. Research on the unique hardware implementation of these techniques is needed.

Radical Innovative RF Circuit Integration.

The ability to combine radio and radar functions in a common, multi-function aperture, operate in multiple simultaneous bands that cover from VHF to Ka-band and provide hemispherical coverage for communication with multiple platforms requires the development of revolutionary technologies that exploit new system concepts in terms of integration and packaging. The present state-of-the-art in circuit integration is based on the conventional MCM concept but leverages on the use of organic materials or other spinned dielectrics for the development of a multilayered interconnect network. This approach has the potential to provide improvements in integration, though it is still limited in performance particularly at high frequencies. The implementation of cost effective RF, microwave, millimeter-wave and optoelectronic systems is constrained by the inability to integrate heterogeneous components in a low cost, high yield, high volume manufacturing process. Radical approaches are needed for packaging of disparate components, e.g., discrete components, heterogeneous technologies, and integrated antennas, either at the chip or package level. Adaptive and reconfigurable components that can provide additional functionality, such as antenna beam scanning or multi-band operation, are essential elements of the problem. Reductions in size, weight and battery requirements and/or improvements in reliability or performance are critical to the Army vision for future combat systems. Concepts should support multiband communications, personal area networks, personal area surveillance and combat ID.

For example, silicon bulk micromachining provides a comprehensive technique for circuit integration, for a very large degree of functionality on a single chip with extremely high density and at a relatively low cost. Si micromachined circuits can be packaged on-wafer and do not require external carriers or external hermetic packaging. Also, the vertically layered structure of the micromachined circuit presents an excellent opportunity for three-dimensional integration, resulting in the potential for substantial reductions in size.

While Si micromachining can provide solution to many integration issues, it may not necessarily be the optimal solution for a given system architecture. The ability to integrate micromachined wafers along with other heterogeneous organic or plastic layers may provide greater degree of flexibility in circuit and package design. In addition, the ability to integrate active components based on diverse substrate material technologies, such as millimeter-wave power amplifier circuits and opto-electronic circuits, into the micromachined structure provides the potential to integrate high level multi-functional systems in a single planar technology.

Other examples include: (a) the integration of multiple micromachined antennas on a non-planar arrangement for hemispheric coverage; (b) the use of heterogeneous materials for the high-density of RF interconnects and DC bias lines; (c) the integration of an on-wafer cooling network to manage thermal dissipation; (d) the use of electromagnetic crystals for dissipation of package resonance and the introduction of additional functionality; and (e) the use of additional layers for individual packaging of MEMS components for device endurance and substantial components isolation. Novel RF systems such as quasi-optical power combining amplifiers, would benefit from a self tuning three dimensional integrated packaging advances.

Controllable and Agile Electromagnetic Structures

The Army has interest in materials and components that can carry out key RF functions in free space or distributed structures rather than integrated circuits. A good example is frequency-agile filtering or power limiting at the antenna level. The combination of 3D periodicity and integrated devices may render new components and functionality for such applications by virtue of controllable dielectric and magnetic properties. This could entail the synthesis of distributed structures having unique material parameter values, such as dielectric constants less than 1 or negative indices of refraction. It may also entail the synthesis of unique values of magnetic permeability.

A key aspect of this topical area is electronic control. High frequency devices, such as Schottky diodes and pHEMTs, can provide rapidly and highly variable capacitance up to frequencies of at least 100 GHz. When integrated with 3D periodic structures, such devices may provide octave or more tunability of filter and limiter function. And because of the distributed nature of the structure, these functions can be carried out with much higher power tolerance, and hence higher dynamic range, than in traditional circuit-based components.

Proposed concepts should go well beyond the past decade of research on 3D periodic dielectric and metallodielectric structures (i.e., photonic crystals) and 2D quasi-optical structures (e.g., spatial power amplifiers), both of which have shown great results at microwave and millimeter-wave frequencies. A generalization of the concepts of photonic bandgap structures, involving periodicity in permeability and even active gain, in addition to the periodicity in dielectric constant.

Nano RF

Investigation of novel concepts in nano-RF technologies may include the research in design and fabrication of structures with an ordered or disordered arrangement of components and devices, much smaller than a wavelength, in a host medium. Such components may be structures of microscopic scale built in the molecular structure of a composite or artificial structure with terahertz, millimeter wave, or microwave frequency resonant characteristics.

Research in ordered or disordered arrays of passive and/or active inclusions with designed dispersive properties may produce unusual applications. Active inclusions may be active particles or microcircuits terminated at active loads. Lorentzian generator description may generate specific electromagnetic filtering, absorption or amplification properties.

Research is encouraged in the design of disorderd band gap structures. Cluster dynamics based on fractal behavior and percolation theory and associated physical phenomena should be pursued. Comparison of ordered vs. disordered systems and their differences as well as equivalences should be determined, especially for curved shapes. Finally, description of the novel nanostructures in terms of effective mu and epsilon dispersive parameters should be realized. Novel applications in smart circuit and antenna devices should be pursued.

2. OPTOELECTRONICS

High-performance optoelectronic devices and systems are essential for the Army to meet the future information gathering, transmission, and signal processing requirements of the objective force. Functions such as very intelligent surveillance and automatic target acquisition; command, control, and communications; and unmanned reconnaissance, must be accomplished with high data rates and with real-time operation which are essential for many such applications. To support the Army's goal to realize the FCS future systems will need to operate at higher speeds, have increased functionality, and have higher levels of integration than present day technology provides. Fundamental research on optoelectronic devices and components is an essential requirement in the development of these future systems.

Novel optoelectronic devices and circuits need to be directed toward specific Army applications to impact the objective force. Requirements include: optical interconnects for high speed, high data rate signal processing; and high volume, rapid access information storage. Advances in optoelectronic devices are needed in order to transmit, manipulate, and process the enormous amounts of signal, voice and video data present in the battlefield. While there are corresponding requirements in the commercial sector, military operations place extraordinary demands on the integrity and performance of the optoelectronic devices. Additionally, semiconductor lasers and detectors are needed to detect chemical-biological agents and are used for imaging, surveillance, and tracking. In all applications, the efficiency, reliability, potential manufacturability and integration of the optoelectronic devices and circuits must be emphasized. High-risk research, with high potential payoff, is necessary to stimulate the development of new technology concepts for these applications.

The ARO optoelectronics program divides into four major areas that are worthy of further investigation for army transformation: detectors- including UV/IR, sources-especially IR, telecom, and visible, modulators and other optoelectronic devices, and optoelectronic integration- including photonic multi-chip module technology. In addition to these four, a strong optoelectronic modeling capability is needed to understand optoelectronic effects in ICs, readout circuits, new laser and detectors, and integrated systems involving optoelectronic devices. This is particularly true when innovative circuit integration techniques are proposed which involve very high densities, three-dimensional integration, or which deliberately violate traditional periodicity or symmetry. In general, new modeling concepts are sought in all of the four sub-areas of optoelectronics. Table 3 shows how each sub-area impacts the development of the warfighting capabilities of the future combat system. Following Table 3 is a detailed description of each sub-area, which includes specific requirements.

Table 3. Warfighting Capabilities vs Optoelectronic Thrust	Detectors	Sources	Other OE Devices	OE Integration
Low power/high efficiency systems		X	X	
RSTA	X		X	X
Chem-bio detection	X			
Threat warning	X	X		
Communications	X		X	X
Information processing	X		X	X
Directed energy lasers	X			X
Sensor protection	X	X		
Combat ID/target recognition	X			X
Smart munitions				X
Countermeasures	X	X		
Guidance control and navigation			X	X
Highly reliable systems	X	X	X	X
Land mine detection	X	X	X	
Bio-function monitor/control	X	X		

Sources

High efficiency semiconductor edge emitting lasers with maximum gain and minimum power consumption are needed for many applications. Highly efficient vertical cavity surface emitting lasers (VCSEL) and two-dimensional (2-D) VCSEL arrays are important for optical processing and parallel optical interconnects. Hybridization of 2-D laser arrays with associated electronics is in demand. Micro-cavity lasers and LEDs also serve as efficient light sources for optical interconnects.

Semiconductor lasers with quantum dot active region and lasers utilizing the photonic crystals and photonic microstructures may lead to development of the improved devices with enhanced performance. Light emitting devices based on polymers or organic materials may offer potential inexpensive means for accomplishing tasks normally associated with semiconductors.

Short wavelength lasers, based on the III-V materials, are particularly important for high-density data storage/retrieval; for displays and chemical-biological detection including high power UV lasers.

Lasers operating at room and near room temperatures at wavelength greater than 1.5 microns (eye-safe) especially at wavelengths in IR atmospheric transparency windows are important for a variety of spectroscopic applications and free space optical communication. Novel laser structures such as intersubband and interband quantum cascade lasers as well as quantum dot lasers may provide long wavelength room temperature operation.

Advances in epitaxial growth techniques including improved methods for self-assembly of materials are required in order to make advances in the field and take advantage of 3-D quantum confinement. Also, potential wide-bandgap laser materials are targeted for advances in growth of material.

Detectors

Future Combat System (FCS) situation awareness will be based on the fusion of data from full-spectrum sensor suites operating at several different wavelengths from the UV to the infrared. Such systems will provide autonomous target acquisition for surveillance, fire control, and identification of friend or foe.

High resolution, high speed, high sensitivity but also affordable multi/hyperspectral and polarization sensitive IR sensors are required for target acquisition, recognition, and identification in the digital battlefield for the future army. This requires the development of large-area multispectral IR focal plane arrays (FPAs) operating at higher temperatures (>120K for TE cooling in vacuum and >190K for TE cooling w/o vacuum). Research opportunities include areas leading to the development of low-cost, large area arrays based on innovative material structures. These may include semiconductor devices operating in the 1-24 micron IR region. For numerous applications, and especially for missile seeker applications, higher operating temperature detectors are required to allow use of thermoelectric coolers, and for LADAR systems very high speed detectors are required. New device concepts and/or materials are needed for these applications.

Development of high performance, solid-state solar blind UV photodetectors is also of interest. Solid state UV/FPAs capable of exceeding the detectivity of current photomultiplier tubes are needed. Such sensors may provide effective early warning and interceptor guidance against missile threats for a wide range of ground vehicle and aircraft. Additional potential applications include atmospheric sensing, tactical communications, and chem-bio detection.

Other E.O. Devices (Optical Switches and Modulators)

Advanced optoelectronic device concepts and the use of novel materials are crucial for providing a revolutionary increase in the overall performance of tactical communications and battlefield assessment. These special needs will not be met by the commercial sector. The future combat system replaces heavy, armored, systems such as the 70 ton tank with a decentralized system of light weight, power efficient, robust sub units that are networked together to provide greater mobility, increased flexibility, and better situational awareness with equivalent fire power. This results in a faster more survivable force. However, the proliferation of platforms with their associated sensors, often video, and their autonomous nature that relies on a network centric approach will place a great burden on the communications infrastructure. RF technologies will have increasing difficulties keeping up with the bandwidth requirements. Networked systems will be susceptible to denial of service and other attacks. Fast optical switches, modulators and novel photonic device approaches offer potential relief to the bandwidth burden, information assurance and network security. These approaches are not intended to displace R.F. technologies, but to reduce bandwidth bottlenecks, and provide additional functionality and flexibility in the network centric battlefield.

The following areas are of special interest:

- High frequency external modulators for lasers
- Ultra-Fast Optical Switches
- Non-reciprocal optical devices, (i.e. novel circulators and isolators)
- Spatial Light Modulators and lightweight, low power retro reflectors
- Optical MEMs
- R.F. Photonic Devices
- Single photon emitters and detectors

To enable these technologies advances in the following areas are critical.

- Engineered Materials such as quantum wells, super lattices, and nano-particles to tailor the band gap to provide wavelength tunability and efficient operation.
- Novel wide-bandgap materials to increase the Curie point of dilute magnet semiconductor devices. Room temperature operation is critical.
- Heterojunction and nanoscale structures with both controlled spin relaxation and g-factors for optically interfaced spin based devices.
- Integration of these materials into planar waveguide and focal plane devices will require incorporating these materials into new device structures and developing new processing methodologies.

As examples of where these technologies may be inserted, one can consider the following applications:

- Point to point Terabit free space optical communication, 0- 10km range.
- Retro reflecting optical modulators to be placed on unmanned vehicles, to provide Identification Friend or Foe, unmanned Vehicle status, and video rate data transfer.
- Short range optical communication channels between autonomous vehicles. This can also provide precision-ranging information between unmanned vehicles
- Secure Communications, using the advantages of highly directional optical beams.
- Ultra-Secure communications using quantum information processing.
- Remote placement of antennas and optical processing of R.F. signals.

Optoelectronic Integration

Novel approaches are needed for successful integration of various optical and electronic materials and devices into optoelectronic integrated circuits (OEIC). The level of integration may vary from using Si as a mechanical substrate for non-Si devices to the on-chip integration of hybrid devices. The preferred integration is through the growth of various materials, including II-VI and III-V semiconductors, on Si. However the complexity and technological challenges of this approach may be cost prohibitive in the near future. However, other possible approaches ranging from novel heteroepitaxial growth techniques, e.g. lateral epitaxial overgrowth, to lift off and bonding (LOB) need to be considered. Other materials of interest include wide-bandgap semiconductors, dielectrics, piezoelectrics, and ferroelectrics. The resulting structures would form the basis of various optoelectronic devices including optical sensors [UV to infrared (IR)], acoustic and seismic sensors, lasers (UV to IR), optical modulators, amplifiers and switches. Degrees of integration advance from the level of devices to multiple components to systems on a chip.

Monolithic Integration and Processing

Monolithic integration provides within a given technology the highest performance, and lowest size, weight and power at minimal cost. Heteroepitaxial growth is of special interest for added OE functionality, such as sensing and signal processing, routing filters, tunable lasers and detectors, high speed optical modulators, and novel network architecture. Besides semiconductor devices, tunable filters based in ferroelectric, magnetic and/or glass substrates are required. Advanced processing technologies are needed at the device and chip levels. Needed research in OE device processing includes: (1) shallow ohmic and rectifying contacts with low-resistivity and low-leakage characteristics, especially for the wide-bandgap semiconductors (2) high-selectivity etching techniques with minimum damage effects, especially for the III-V compound semiconductors, (3) in-situ monitoring techniques for precise control of material deposition and etching, and (4) self-assembled patterning techniques. Techniques for mask-less and resist-less fabrication are needed to fabricate integrated nanostructures and associated optoelectronic devices, such as waveguides, vertical-cavity surface-emitting lasers (VCSELs), and gratings. Defect reduction in nanolithography is a critical issue. Self-organized growth of low dimensional structures for nano-scale devices (~20 nm) needs further research.

Hybrid Integration

Mature technologies consisting of optimized components based on different material systems can be hybridized to achieve new system level functionality that is not currently possible via monolithic integration. This approach can take advantage of existing foundries and established design rules. Examples include: Si CMOS electronics, III-V optoelectronics, II-VI or III-V FPAs, Si MEMS, and Si SLM.

High performance optoelectronic elements need to be integrated with Si IC technology to facilitate dense input-output functions as well as for high-bandwidth intrachip communication.

Further research is required on novel device concepts relating to mixed-material architectures and on large-scale IC architectures that take advantage of the wide-band communication between parallel subsystems on a Si chip. The parallelism and bandwidth of optics needs to be coupled with the programmability and functionality of VLSI circuits. Improvements in the integration of optical devices, such as VCSELs, with Si ICs must be made for signal and image processing applications.

Advanced Integration

Advanced integration must take into consideration the challenges of both the fabrication and packaging of OE chips to achieve the full advantages of mixed photonic/electronic device integration. Applications include RF Photonics, chem-bio detection, smart pixels, adaptive optoelectronic imaging, etc.. Research is required in advanced packaging concepts, including novel concepts such as self-assembly, for the efficient integration of diverse chip system technologies into a single system. This will require materials and processes that allow simultaneous multi-chip placement and simultaneous multi-bond creation to obtain the type of cost efficiencies associated with chip integration processes. One example is RF Photonics in phased array radar to achieve improved isolation and superior true time delay performance. Such hybrid and integrated systems require functional substrates that facilitate low latency interchip interconnections. Modeling of these multi-chip systems is a particularly complex problem that can benefit from novel approaches. These advanced concepts also enable 3-D packaging approaches. 3-D packaging could be useful for systems where electronic controllers for MEMS devices, optoelectronic devices, sensors, or antennas are integrated on the same substrate with power transducers and system outputs.

3. SOLID STATE AND HIGH FREQUENCY ELECTRONICS

High-performance electronic, optoelectronic and mixed technology systems are essential for the Army to meet it future information and processing requirements. Functions such as very intelligent surveillance and target acquisition; command, control, and communications; electronic warfare; and reconnaissance, must be accomplished with high data rates and real-time capability essential for many such applications. To support the Army vision of Objective Force and Future Combat System, these systems will need to operate at much higher speeds and frequencies, have greatly increased functionality, and have much higher levels of integration than present day technology provides. Fundamental research on Solid State Devices & High Frequency Electronics is an essential requirement in the development of these future systems.

Advanced electronic device concepts are crucial for providing a revolutionary increase in the overall performance for communications, data transfer, and information processing needs underlying the Objective Force vision. To achieve this goal, two distinct classes of electronic devices are of major interest: devices with high speed and low power for wireless communication and low noise, high efficiency, high frequency devices for signal processing. High-risk research, with high potential payoff, is necessary to stimulate the development of new device concepts for these applications.

With the Army's increasing emphasis on Networked C^3, Advanced Sensor Function, Organic/Inorganic RSTA, Indirect Fire Capability and FCS Sensor Function, research in the areas of electronic, optoelectronic and mixed technology devices and circuits is critical. However, novel electronics-based sensor systems need to be directed toward specific Army applications to impact this major focus. Envisioned Army requirements include: high speed, high volume communications; optical interconnects for high speed, high data rate signal processing; and, high volume, rapid access information storage. Major advances in heterogeneous devices and technologies are needed in order to transmit, manipulate, and process the enormous amounts of signal, voice and video data present in the battlefield. While there are corresponding requirements in the commercial sector, military operations place extraordinary demands on the integrity and performance of electronic/ optoelectronic devices. Additionally, highly integrated, mixed technology circuits with higher functionality are required to address the specific needs of the Army, such as the optical control of microwave antennas and infrared target recognition. In all applications, the efficiency, reliability, potential manufacturability and integration of the devices and circuits must be emphasized.

The research thrusts identified in this section are shown below:

- Thrust SS/HF-1: Novel Materials for Advanced Electronics
- Thrust SS/HF-2: Nanoscale Processing and Fabrication Science
- Thrust SS/HF-3: Nanoscale Physical Modeling and Advanced Simulation
- Thrust SS/HF-4: Nanoscale Science and Technologies
- Thrust SS/HF-5: Terahertz and Ultrafast Electronics
- Thrust SS/HF-6: Advanced Device Concepts
- Thrust SS/HF-7: Mixed Technologies - Electronics, Photonics, Acoustics and Magnetics
- Thrust SS/HF-8: Heterogeneous Devices and Technologies
- Thrust SS/HF-9: Micromachined Devices
- Thrust SS/HF-10: Ultra-Low-Power Technology

Table 4. Warfighting Capabilities vs SS/HF Thrust	1	2	3	4	5	6	7	8	9	10
Low power/high efficiency systems	X	X	X	X	X	X	X	X	X	X
RSTA	X	X		X	X	X	X	X	X	X
Chem-bio detection	X	X	X	X	X	X				
Threat warning	X	X			X	X	X	X	X	X
Communications	X	X		X	X	X	X	X	X	X
Information processing	X	X	X	X	X	X	X	X	X	X
Directed energy lasers	X	X			X	X	X	X		
Sensor protection	X	X				X	X	X		
Combat ID/target recognition	X	X	X	X	X	X	X	X	X	X
Smart munitions	X	X		X	X	X	X	X	X	X
Countermeasures	X	X		X	X	X	X	X	X	X
Guidance control and navigation	X	X		X	X	X	X	X	X	X
Highly reliable systems	X	X		X		X	X	X	X	
Land mine detection	X						X	X	X	
Bio-function monitor/control	X	X	X	X	X	X	X	X	X	X

Table 4 illustrates the major interactions between the research thrusts for Solid State & High Frequency Electronics and specific Objective Force and FCS warfighting capabilities.

These thrusts will now be defined in detail.

Thrust SS/HF-1: Novel Materials for Advanced Electronics

Advanced electronics of the future will rely heavily on new materials and novel material systems, such as multilayer configurations of metals, insulators, and semiconductors with nanoscale dimensions. Mixing and matching materials is the main key to new devices that combine technologies. Here, the ability to combine metals, magnetic materials, ferroelectrics, and other dielectrics with semiconductors are critical processes. In addition, the more difficult problem of growing semiconductor epilayers on these materials is necessary for new heterostructure devices. Electronics applications will continue to be a scientific force for the realization of new materials for Future Combat Systems through a better understanding of physical, chemical, and thermodynamic properties. These advanced material structures will enable innovations in devices, circuits, and systems through the use of sophisticated growth and process technologies, such as MBE, OMCVD, and the evolution of other atomic scale synthesis methods. Research on these methods and revolutionary new growth techniques will facilitate the capability for engineering material systems with precisely proscribed properties and controlled surfaces and interfaces, varying from hyper abrupt monolayer structures to a variety of graded interfacial profiles that are required of future electronic components.

Continued scientific achievements in advanced electronic materials research will also provide the foundation for attaining a comprehensive data base for multilayer, multicomponent materials systems needed for the characterizing, simulation and modeling of new device and materials concepts. These novel engineered materials systems are required for: (1) narrow band gap materials for low power, high speed electronics and long-wavelength lasers; (2) wide band gap materials for high temperature, high power electronics and short-wavelength light emitters and lasers; (3) mixed semiconductor structures consisting of lattice-matched or strained epilayers of materials grown on large area substrates for sensing subsystems; (4) heteroepitaxial materials and metal-insulator-semiconductor structures for single-electron transistors and nanoelectronics; (5) nanometer scale semiconductor and ferromagnetic multilayers and nanocomposites comprised of semiconductors and metals or magnetic materials for ultra fast terahertz electro-optics and spintronics; and (6) monolayer growth techniques for new types of semiconductor-atomic superlattices. In support of the growth techniques for engineering new materials, research is needed in precise atomic layer (sub-monolayer) control; in-situ monitoring and automatic control with wide dynamic range; selective area epitaxy and overgrowth in nanoscale areas; growth on pre-patterned substrates; large area chemical composition and doping uniformity and control; and in-situ material characterization at the atomic level over large areas.

Future Combat Systems for the Army will also require the integration of biological mechanisms into electronic and optoelectronic materials for novel sensing and processing systems. For example, research fields such as biomimetics and biomechatronics are emerging which establish new materials requirements that can result in electronic and optoelectronic analogs of biological systems. These system requirements will be constructed on the advances that result from the growth and engineering of advanced materials. The microelectronic or optical interaction with internal cellular processes provides the opportunity to monitor, control, and interface electronic and biological systems for applications such as the cellular functions of diagnosis, healing, reproduction, cell mobility, or metabolism. In addition, such control may have electronic functional applications such as the control of DNA type computing. Biological MEMS applications may provide unprecedented control and sensing of in vitro bodily processes and functions. Ultra-high frequency acoustic wavelengths can be comparable to the size of a cell, opening opportunities for selective interrogation and manipulation.

Thrust SS/HF-2: Nanoscale Processing and Fabrication Science

Nanoscale devices will require unprecedented capabilities in processing and fabrication. Atomically controlled surfaces and structures with tolerances of ~ 0.1 to 1 nm in three dimensions will be required. New processing techniques are required for selective etching, deposition and doping of multi-semiconductor material systems, such as pseudomorphic structures, mixed lattice-matched and lattice-mismatched compounds and for controlling amorphous-crystalline interfaces. Materials processing must be accomplished with minimal surface damage and growth uniformity over large substrates. New materials, ranging from biological to magnetic must be incorporated with semiconductors and insulators with three-dimensional, nanoscale control. Specific materials processing research includes: (1) low-resistance, very shallow (~ 1 nm) ohmic contacts; (2) high selectivity etching techniques with minimum surface and sidewall damage effects; (3) *in-situ* monitoring and metrology techniques for precise, real-time control of material deposition and etching; (4) *in-situ* monitoring techniques for precise placement and real-time control of dopants and impurities; (5) surface cleaning and termination processes for repeatable interface generation at the nanoscale; and (6) development of compatible fabrication processes for diverse technologies – i.e. multiple semiconductor families, biological species, magnetic materials, etc..

Advances in lithographic and self-assembly transverse and 3D patterning at the nanoscale will be required. Serial, direct-write capabilities such as electron-beam lithography and scanning-force microscope manipulation will continue to be invaluable research tools, but are unlikely to provide the numbers of nanostructures required for either scientific investigations of large-scale array/ cooperative effects or for transitions to application. Fundamental investigations into parallel lithographic and self-assembly approaches will be required. Both interferometric and nanoimprint (and variants) lithography approaches have shown promise for scalable, large area nanostructure fabrication. Three-dimensional, nanoscale fabrication is a largely unmet need that could enable fundamentally new functionalities and devices.

Self-assembly (SA) takes advantage of physical and chemical nanoscale processes to provide an alternative technique that has already had substantial success at the nanoscale. A particularly important class of novel SA techniques centers around the creation of quantum dot and dash arrays by the interplay of strain and surface tension in the epitaxial growth of semiconductor heterostructure systems with length scales in the 1- to 20-nm range. Other interesting approaches are chemical synthesis and precipitation, and inhomogeneous phases in multi-component solute/surfactant systems. Existing approaches are well adapted to creating nanoscale features but improvements are needed in control of the size distribution and the long-range order. High priorities for research in the near future should focus on:

- Extend existing and develop new SA growth techniques for heterogeneous materials, devices and electrical/optical interconnects;
- Explore the combination of SA (for nanoscale structures) with nanolithographic approaches (for long-range order);
- Develop new methods to probe and excite these nanostructures based on e.g. near-field optical and atomic force microscopes;
- Develop new material and device ideas and proof-of-principle structures that are particularly suited to SA structures;
- Research on extending recently developed SA-based devices to operation at room temperature and above.
- Research on use of nanostructures for device application as catalytic surfaces and chemical/biological detectors.

Thrust SS/HF-3: Nanoscale Physical Modeling and Advanced Simulation

The vast potential of a fully developed nanoelectronic-based technology is well recognized. The possibilities for enormous increases in functionality, integration and speed offered by molecular-level systems motivate a detailed investigation of nanoscale elements, devices and systems. Furthermore, the one thousand times reduction in electronic feature sizes from present micron levels to nano-scales may translate into greatly enhanced capabilities for future military defense. However, while currently there is a strong and growing interest in nanoscience and nanotechnology, there are major scientific and engineering research challenges that must be addressed before a robust nanoscale capability can be realized. Specifically, research into nanoscale electronic and optoelectronic devices and systems has made significant advances in recent years. However, bridging the intellectual gap from the nanoscopic to the microscopic presents new and unprecedented challenges. For example, nanoscale elements and devices present unique, and almost insurmountable problems, for experimental probing and characterization. Furthermore, when experimental tools of sufficiently small size and precise positioning capability are developed, it is presently not possible to completely predict what perturbation effects such measurements will have on the nano-systems under test. Therefore, these problems represent a fundamental scientific bottleneck and demand the development of a first-principles theoretical and physics-based modeling capability to accurately reveal both the quantum mechanical interactions at the molecular level and the influence of the macroscopic environment. In addition, a nanoscale technology will present an extremely dense and complex functioning system. Hence, any useful theoretical analysis can only be achieved by the robust implementation of simulation tools on a high performance computational platform.

Therefore, collective research into nanoscale physics and advanced simulation techniques is needed to address the key modeling and simulation aspects of nanoelectronic components, devices and systems. The central goal must be to develop simulation and modeling methods that adequately capture the underlying physical principles relevant to nanodimensional and temporal scales, and provide a vehicle for exploring physical and chemical consequences of nanodimensional processes. This multidisciplinary research thrust will need to bring together varying expertise from physics, chemistry, electronics and computational science to realize a physically accurate and robust approach for the analysis of molecular-level electronic systems. A complete theoretical capability for the full characterization of nano-systems has the potential to facilitate new and unprecedented capabilities for integrated electronic sensing, high-speed computations and rapid information processing.

Thrust SS/HF-4: Nanoscale Science and Technologies

Nanotechnology offers new paradigm to pursue beyond "the silicon roadmaps" devices and circuits to circumvent the limitations in conventional electronics, i.e. capacitive delay and parasitics, power dissipation per functional area, and the constrain of "real-estate gobbling" device isolation. The ultimate goal is to achieve ultra fast, ultra high density, low power consumption, integrated sensory, logic, memory, and power source system.

Rapid progress in non-traditional semiconductor processing techniques and new materials such as self-assembled quantum dots, carbon nanotubes, and molecular electronics, open new ways of construction and assemble nanoscale devices and systems. Progress in conventional semiconductor fabrication technology also leads nanoscale device components. The fundamental quantum nature of nano systems (such as energy levels quantization and coherence quantum states) promises revolution advances in new ultrafast low-power processors and ultra-dense memory elements, and new paradigm of quantum computing. The strong coupling of quantized charge and spin at nanoscale provides a natural platform for integration of multifunctional integrated electronic, magnetic and optical devices.

Numerous nanometer-scale devices have been successfully demonstrated; these include self-assembled quantum dots; room temperature single electron FET and diode based on carbon nanotubes, controlled doping and construction of functional junctions in nanotubes and nanowires. Other quantum devices have been envisioned and can be fabricated with present technology. Research is required to realize a number of goals such as: synthesis and characterization of nano structured materials; method of manipulation and construction of nano structures; evaluation of new nano electronic devices elements; advanced enabling tools for individual and collective devices and systems.

Pursues of molecular electronics that is, the use of nanomanipulated and engineered atomic and molecular systems to achieve integrated sensory and electronic functionality, offer another possibility for ultra fast, ultra low power demand and dissipation devices. This requires the ability to conceptionalize, design, fabricate, and characterize molecular components, and integrate components to achieve soldier-focused embedded functionality.

NEMS – Nanoelectromechanical systems need to be pursued to explore the possibility of integrating multiple functions into monolithic structures including electronic, electromagnetic, and mechanical response to achieve novel components for autonomous functionability.

Portable power source is bottleneck for soldier-centric electronic warfare. Nanostructured electrochemical active materials for batteries and fuel cells may provide a breakthrough to high density and high performance portable power source and potential of integrated device and power system.

Fundamental physical limitations of the operational range of electronic devices need to be investigated. Exploration of nanoscale device structures and self-assembly techniques may provide alternatives to scaling of conventional lithography. In this context, novel device concepts based on atom manipulation are promising approaches. Research into non-equilibrium phenomena and dissipative processes for quantum-confined charge carriers in nano scale device structures is needed.

Within the field of nanometer-scale devices, the limiting case of single-electron devices needs to be better understood in terms of ultimate utility and the effects of device-to-device coupling.

Realizing the full opportunities provided by these structures will also necessitate and stimulate further technological breakthroughs.

Modeling and simulations, such as ab initio calculations and molecular dynamics simulations, of nanoscale process and structures, should provide guide for potential novel nano devices and configurations, and for pursuing realistic goals and opportunities.

Thrust SS/HF-5: Terahertz and Ultrafast Electronics

Semiconductor devices face fundamental limits in their power, efficiency, and sensitivity when pushed to operate at frequencies approaching 1 THz or at time scales below 1 ps. This is largely because of RC times, transit times, and scattering processes inherent to the solid state (e.g., phonons) that are difficult to suppress in traditional semiconductor device structures operating at room temperature. To improve device performance, the Army is interested in new device and circuit concepts, including quantum transport devices such as resonant tunneling structures, and quantum-transition devices in which photon emission can occur through intersubband transitions between quasi-bound states. It also includes traditional devices with revolutionary circuit and packaging techniques to improve performance. The components of particular interest are electrically-driven room-temperature sources, cw or pulsed, operating between ~ 0.1 and 10 THz. Innovative and novel methodologies should be explored until an effective approach is discovered or developed. Here, the development of efficient sources and integrated semiconductor-based components and systems is a priority.

A key application of interest for terahertz and ultrafast electronics is battlefield remote sensing of biological agents. Recently it has been shown that terahertz radiation interacts with living matter via low frequency vibrational modes. The absorption and emission of photons by these modes may be strong enough to make instantaneous detection and identification of bacterial warfare agents possible. A key aspect of all these applications is all-weather and all-situational capability. Existing devices such as the JSLSCAD that use IR or shorter wavelengths to detect biomolecules, become blind in inclement weather or in fog or dust.

A second class of application is point detection of biological/chemical agents and explosives, such as RDX and TNT that also interact with THz radiation via low-frequency vibrations and rotational modes. Rapid, unambiguous identification of chemical agents, precursors, and degradation products is required in many areas of the DoD including treaty verification and counter-terrorism. The ultra-high resolution offered by THz spectroscopy may provide this rapid identification even when the substance is in a complex mixture.

A final, and possibly even more far-reaching application of THz electronics, is in the development of concepts for extending ultra-wideband sensing and communications. Indeed, the fusion of an advanced THz-frequency sensing capability with conventional sensor-network communications has the potential for significantly enhancing the network-centric capability of the Army's Future Combat System in the future. Here, THz electronics will collectively impact spectroscopic sensing, radiometric imaging and data transmission/processing. Furthermore, commercial local-area-wireless networks can already be envisioned at frequencies as high as 400 GHz, therefore, THz electronics has a strong duel use potential.

Thrust SS/HF-6: Advanced Device Concepts

Novel mechanisms for control of electron transport and optical interaction phenomena are the key to the next round of major advances in electronic devices. There is a continuing need to investigate fundamental phenomena and operational physics that can extend the limitations of electronic device performance. There is much interest in devices that can operate beyond the current limits of power and frequency with improved efficiencies and low-power consumption. Research into novel devices based upon quantum-confined structures with nonequilibrium and dissipative electron processes in low-dimensional device structures is needed. Novel contact and interconnects to nanoscale devices is of particular importance. Physics and modeling of nanoscale devices and advanced synthetic materials will be an imperative to establish future components. In addition, novel advanced devices based upon wide bandgap semiconductors, such as SiC and nitride-based compounds, offer the potential for significant advances both in high frequency and high power performance. Devices based upon AlGaN/GaN heterointerface offer the potential for an order of magnitude improvement in device performance.

Novel devices based on mixed-mode principles portend numerous multi-functional information handling applications. Whereas, many current devices depend primarily upon a single phenomenon for their operation, mixed-mode devices exploit a complexity of interactions between a variety of fields, including quasi-static electric and magnetic, electromagnetic, optical and quasi-optical, acoustic, thermal, and elastic. Advanced device concepts for use by the future Army are needed, including: efficient, low power components; both compound semiconductor and silicon-based heterojunction devices; single-electron charging effects and quantum devices; ultra high speed optoelectronic devices; terahertz device technology; micromechanical and microphotonic, ultraviolet, visible and infrared integrated sensors; vacuum microelectronic device structures; devices based on high temperature superconducting materials; and molecular electronics. In this framework, wafer-scale probing of high speed and high frequency devices and electrical characterization of ultra small structures are important topics. The use of scanning probes, such as scanning tunneling microscopes, ballistic electron energy microscopes, atomic force microscopes, scanning magnetic force microscopes, and scanning near field optical microscopes may provide useful solutions.

Improved high-temperature, high-power electronics are needed in order to meet a variety of future applications. This includes compact power switches as well as high-temperature, high-power integrated circuits, and high-temperature control circuits. The development of high-temperature, high-power electronics will require: the development of new techniques of materials growth for SiC-based, GaN-based, and composite materials; the development of reliable device fabrication techniques with emphasis on high-temperature stable ohmic and Schottky contacts, and passivation; the development of new unipolar and bipolar devices; the development of high-temperature packaging; and the development of CAD modeling and simulation tools and testing and characterization techniques for high-temperature, high-power electronics. Realization of improved performance requires the operation of advanced devices in a circuit environment. Therefore, research of device/circuit interactions is of fundamental importance.

Thrust SS/HF-7: Mixed Technologies - Electronics, Photonics, Acoustics, Magnetics, and Bioelectronics

Mixing and matching electronics, photonics, acoustics, magnetics, and biological science offers the potential to bring improved performance and new functionality to information processing, storage and communication technologies. The modulation of optical signals at RF frequencies provides the opportunity for novel analog signal processing of RF signals using optoelectronic devices and circuits. Potential applications include electronic warfare, optically controlled phased arrays, and compact processing of radar and communications waveforms. Maturity of semiconductor nano- and microstructure growth and ultrafast optical and other high frequency microwave, millimeter and submillimeter wave technologies present opportunities to expand all-optical signal processing. Engineered materials offer enhanced microwave/optical non-linearities important for direct modulation of optical signals at terahertz frequencies. These materials and device structures will include quantum structures resonant at both modulation and carrier frequencies and active devices like semiconductor optical amplifiers resonantly driven at ultrahigh frequencies. The knowledge base required for successful development of ultrahigh frequency electro-optic modulators involves theoretical modeling of the high frequency dynamics of quantum structures driven far from equilibrium, growth, processing and fabrication of terahertz/optical modulators and experimental measure of modulation dynamics at ultra high frequencies. Surface acoustic waves are the basis for current sophisticated signal processing. Surface acoustic waves in compound semiconductors opens the possibility of exploiting the interaction of optical fields and surface acoustic waves by creating, trapping and moving spatially separated electrons and holes to encode and process information.

The monolithic integration of magnetics and semiconductors electronics will make possible new schemes for information processing and storage. Non volatile, on chip, information storage follows but breakthroughs will occur if magnetic configurations can be controlled with applied voltages or laser radiation rather than local magnetic fields produced by currents. Long-lived spin polarization that can be transported over macroscopic distances and through interfaces is potentially important for readout. If applied voltages control the magnetic coupling of two films the magnetostatic mode dispersion and propagation of spin can be modulated. Scientific issues focus on spin transport and magnetic interaction in applied electric fields and across junctions and how they are related to material and material structure. Materials issues address novel heterostructures comprised of electronic semiconductors and magnetic metals or magnetic semiconductors. The integration of magnetics and semiconductors will be critical to the development of monolithic terahertz systems for military communications and sensing applications. For example, the integration of magnetic structures with micromachined waveguides and components will allow the direct integration of high performance terahertz circulators and isolators, key components of microwave systems. Such advances would lead to integrated terahertz sources and communication systems with much greater performance, efficiency and compactness.

Lastly, the use of acoustic and seismic signatures provides a means for the detection of moving targets by unattended ground sensors. Novel active devices can provide advantages in signal to noise ratio and sensitivity. The selective detection of voices in a crowd and the automatic translation of languages require the very high signal to noise characteristics. Acoustic and seismic techniques may also be feasible for long range communications and communications into tunnel systems.

Thrust SS/HF-8: Heterogeneous Devices and Technologies

Future Army battlefield scenarios are anticipated to require systems employing devices fabricated from diverse technologies and operating using disparate physical processes, but functioning as a seamless operational unit. Devices of this type might be needed, for example, in the battlefield scenario requiring integration of multiple sensors, A-D conversion, digital computation, D-A conversion and output control signal delivery. In many cases the optimum system solution will require heterogeneous devices, that is, devices utilizing different materials and operating on different physical principals. These devices might, for example, employ non-silicon based light emitters and detectors fabricated on silicon signal processing devices. Or they might combine fundamentally different technologies such as MEMS and electronic signal processing, or biosensors and silicon readout circuitry. In most cases these heterogeneous devices will need to be monolithic (all technologies fabricated together on a single substrate) for optimum performance. In very specialized instances the optimum solution might employ a hybrid configuration with some separate devices assembled in a very close proximity configuration. In all cases, the heterogeneous device will be characterized by the combination of technologies providing a unique function or superior functionality to the mere interconnection of discrete components. The superior functionality can be in any one or a combination of features such as speed, sensitivity, low power, small size, low cost and high reliability.

Significant research in device physics, processing, modeling and system simulation is required to meet the Army's heterogeneous device needs for the battlefield of the future. The following is a representative (but not comprehensive) list of research needs in this area.

Research is required on:

- Integration of hybrid devices based on mixed compound semiconductor structures on Si;
- Novel device concepts relating to mixed materials and unique device architectures employing mixed materials;
- Novel very large scale integrated circuit architectures that take advantage of the unique capabilities (wide-band communication, low power signal transfer, etc) between heterogeneous subsystems on a Si chip.
- Advanced concepts for partitioning total system function into multi-chip functional elements that optimize performance based on heterogeneous devices.
- Advanced packaging concepts, including novel concepts such as self-assembly and 3D, for the efficient integration of heterogeneous chip technologies into a single system with enhanced performance.

New approaches to materials processing, such as epitaxy (including selective epitaxy), and low temperature processing, wafer bonding, and novel fabrication techniques to improve functionality, yield and reliability of heterogeneous devices.

Accurate and advanced process simulation and Computer-Aided-Design (CAD) modeling tools for cost effective fabrication, design, parameter extraction, and characterization for novel heterogeneous devices.

Thrust SS/HF-9: Micromachined Devices

Micromachining technology has enabled a diverse class of field-controlled, mixed-mode interaction devices, most often referred to as MEMS devices or microelectromechanical systems. MEMS devices exploit forces of electromagnetic, optical, thermal, chemical, biological, and elastic processes to sense, actuate, or convert between these energy types. Microelectromechanical systems devices tend to be highly efficient and lower power than the devices they replace, but their most important advantage comes from enabling new functionality in electronic systems. MEMS devices are presently being used in inertial navigation systems, sensors, tunable RF elements, switches, and in several biomedical applications among many application areas.

Early research focused on processing, exploring novel device architectures, and in modeling. New developments are possible in these areas exploiting current and future microprocessing technologies to create novel devices capable of operating under the influence of various external and internal fields and stimuli. The research in this area should focus on ways to harness these forces, to model the interactions between these forces and electronic devices or materials, and to develop novel device concepts exploiting these interactions. In addition, there are several fundamental issues related to removing barriers to MEMS devices in applications that require basic research results: increasing device reliability and lifetime, exploiting the sensing power of MEMS devices, packaging for harsh environments, developing new multi-modal capabilities. Army applications can benefit from new capabilities in electronic and electromagnetic devices, control systems, energy conversion devices, electromechanical, chemical and biological sensors. The Army is specifically interested in sensors to increase the information available to soldiers and commanders, low-loss switches and RF modulators impacting future communication systems, mixed modality applications such as microfluidics and microactuators for controls and biosensing, and power control and generation.

MEMS are an important technology area and will impact:

- Compact Power Sources
- Enhancing Soldier Performance
- Microminiature/Multifunctional Sensors
- Intelligent Systems
- Mobile Wireless Communications
- Smart Materials and Structures

Thrust SS/HF-10: Ultra-Low-Power Technology

The battlefield of the future imposes the competing requirement of increased mobility against the equally important need for increased complexity and sophistication of electronic equipment. These requirements taken together demand that the power per function decrease significantly. Although the 1999 National Technology Roadmap for Semiconductors (NTRS) projects decreasing power per function for commercial devices, it actually projects a continued increase in power consumption at the chip level up to year 2012. Therefore, it is expected that the Army requirement will not be satisfied using commercial approaches. The Army will keep abreast of commercial low power advances, but must also prepare for the more stringent requirements of the battlefield scenario. The research in this thrust emphasizes ultra-low-power devices and techniques other than those being pursued by industry as part of the established NTRS thrust. Instead, the thrust of this research is on novel devices --- such as quantum-based --- devices that portend applications in alternative ultra-low-power scenarios. This research also emphasizes development of alternate energy sources and power management. The following is a representative (but not comprehensive) list of research needs in this area. It should be noted that some of this research-need overlaps with the advanced device area. The distinguishing feature of research in this thrust is the concentration on low power aspects of technology, which includes:

- the development of novel ultra-low power devices with different geometries that decrease parasitics and eliminate or drastically reduce non-ideal effects as well as devices with a higher functionality that can replace several transistors in an integrated circuit;

- new solid state non-volatile memories to replace hard drives, CD-ROMS and DVDs;

- new circuit solutions such as the development of charge-conserving circuits;

- new approaches to interconnects linked to new approaches in system architecture, such as combining conventional and optical interconnects;

- new approaches to thermal management, including energy recycling;

- the development of improved photovoltaic energy sources integrated with the system and with an energy storage system;

- the development of non-conventional energy sources, such as energy harvesting from human sources, or relying on satellite generated microwave beams;

- circuits that turn on and off on demand so standby current usage is minimized.

APPENDIX

2001 ELECTRONIC DIVISION
RESEARCH STRATEGY PLANNING WORKSHOP
AGENDA

January 16, 2001
1500 Registration
1700 Cash Bar
1800 Dinner
1900 Dinner Speeches
    Welcome and Introduction
    Science of Terahertz and other Ultrafast Devices - James Allen

January 17
0730 Breakfast
0830 Presentations
    Overview, goals, instructions
    Future Combat System – LTC Brad Tousley
    Army Scientific Research Objectives – Mike Stroscio
1000 BREAK
1030 Presentations (cont)
    SOLID STATE - Marc Kastner
    Spin Electronics – Stuart Wolf
    New Concepts in Adaptive RF Multifunctional Circuit Architectures - Linda Katehi and Michael Steer
    Transformation of the Objective Force - Col. William Bransford
1230 Lunch
1330 Nanoscale Electronics…: Good or Bad? - Raphael Tsu
    BREAKOUT GROUPS/ Instructions
    Optoelectronics (Gerhold/Clark)
    Electromagnetics and MMW Circuit Integration (Harvey)
    Solid State (Stroscio)/High Frequency Electronics (Woolard)
Dinner (open)

January 18
0730 Breakfast
0830 PRELIMINARY REPORT OUT
0930 BREAKOUT GROUPS
1230 Lunch
1330 BREAKOUT GROUPS
1530 REPORT OUT
1700 ADJOURN

WORKING GROUPS

Solid State and High Frequency Electronics
Dr. Dwight Woolard, ARL/ARO –Co-Chairman
Dr. Jagadeesh Pamulapati, ARL/SEDD – Co-Chairman
Dr. Michael Stroscio, ARL/ARO – Co-Chairman
Professor Robert Trew, Case Western University
Professor Michael Littlejohn, UNC-Asheville
Professor Ray Tsu, UNC-Charlotte
Professor Steven Brueck, U. of New Mexico
Professor Jerry Iafrate, U. of Notre Dame
Professor James Allen, U. of California-Santa Barbara
Professor Elliott Brown, U. of California-Los Angeles
Professor Sadik Esener, U. of California-San Diego
Professor Thomas Crowe, U. of Virginia
Professor Jianping Lu, UNC-Chapel Hill
Dr. James Jensen, Soldier Biological & Chemical Command
Dr. Charles Britton, Oak Ridge National Lab.
Dr. Joseph Mancusi, Microelectronics Center of NC
Dr. Harold Hosack, Semiconductor Research Corporation
Dr. Edgar Martinez, DARPA

Optoelectronics
William W. Clark, III, ARL/ARO Co-chair
Michael Gerhold, ARL/ARO, Co-chair
Nadia El-Masry, NCSU
Steve Chou, Princeton
Hung-Dah Shih, DRS Technologies
Richard Anderson, NSF
Greg Salamo, U Ark
George Simonis, ARL-SEDD
Herbert Pollehn, ARL-SEDD
Robert Kolbas, NCSU
John Muth, NCSU
Jim Ratches, NVESD
Gregory Belenky, SUNY Stonybrook
Stuart Wolf, DARPA
Gerry Iafrate, U ND

Electromagnetics
Dr. James Harvey ARO Chair
Professor Tatsuo Itoh, UCLA
Dean Linda Katehi, University of Michigan

Professor Henry Bertoni, Polytechnic University
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