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DEPARTMENT OF DEFENSE
ADVISORY GROUP ON ELECTRON DEVICES
WORKING GROUP A (MICROWAVE DEVICES)
WORKING GROUP B (MICROELECTRONICS)

SPECIAL TECHNOLOGY AREA REVIEW
ON
Silicon Germanium Technology

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Foreword

The DoD has been assessing technologies that have potential for decreasing the cost of its systems by leveraging the commercial world. For this reason, Working Group A (Microwaves) and Working Group B (Microelectronics) of the DoD Advisory Group on Electron Devices (AGED) held a Special Technology Area Review (STAR) on January 19, 1994, in the area of silicon/germanium (Si/Ge) electronic devices. Subsequently, a mini-STAR was held on June 14, 1995, to provide an update to the January, 1994, information. A report on the 1995 mini-STAR is included as an addendum to this report. For the most part, Si/Ge devices offer the promise of utilizing cost-effective standard silicon (Si) processing capable of leading to affordable Si/Ge components in volume quantity. However, unlike most standard Si technology, higher performance Si/Ge technology could prove cost-effective in those DoD microwave frequency/high speed microelectronics applications that require less than the highest performance available, say, from GaAs. The future cost of Si/Ge parts is a complicated issue, but it is a current belief that the principal benefit of Si/Ge technology will be low cost coupled with "better than silicon" performance (in other words, potentially a higher-than-silicon performance return for each DoD dollar invested). The future of Si/Ge is closely tied to unresolved infrastructure issues and, if industry fails to address these issues (for example, the development of critically lacking Si/Ge infrastructure production tools), the future merchant market might constrain Si/Ge to a niche technology role. To-date, the primary investment in Si/Ge technology has occurred in the commercial arena. Si/Ge electronics technology can have other advantages besides increased performance and low cost. Some of these advantages will be discussed in this report.

The fact that near term Si/Ge technology development has focused upon commercial applications has, in part, led to the currently held view that Si/Ge is mostly a commercial end use technology. In the report to follow, current performance results and applications for Si/Ge components will be presented with a view toward downstream benefits for the DoD. Also, in keeping with present DoD interest in dual-use technology, this report will touch upon the economic implications of Si/Ge including both military and commercial markets as well as potential foreign competition.

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Executive Summary

This report details the findings and recommendations of Working Groups A (Microwaves) and B (Microelectronics) of the DoD Advisory Group on Electron Devices (AGED), that resulted from information presented at a January 19, 1994, Special Technical Area Review (STAR) on silicon/germanium (Si/Ge) technology. In addition, a mini-STAR was held on June 14, 1995, to provide updated information. A report on this mini-STAR is included as an addendum to this report. Si/Ge offers the promise of effectively leveraging low cost, commercial, silicon processing technology to provide affordable volume-quantity Si/Ge components that have significant performance advantages over all-silicon components. This material could prove cost-effective for DoD microwave/high speed microelectronics applications which require better-than-silicon performance but not the highest performance levels available, that might be obtained from, for example, gallium arsenide (GaAs). Principal findings and recommendations determined from the STAR are as follows:

- Si/Ge is principally a commercially-oriented technology with spin-off potential for military requirements. To-date the primary investment in Si/Ge has been borne by a few commercial interests.

- Future success in both commercial and military Si/Ge technology depends upon resolving infrastructure issues (especially CAD software related) and upon the ability of Si/Ge technology to keep pace with future manufacturing developments in silicon components/technology.

- The DoD should principally rely on the commercial world for manufacturing advances, infrastructure development and silicon compatibility of Si/Ge technology that can lead to commercial Si/Ge products (with military spin-off) that DoD can leverage for its use.

- The highest near-term Si/Ge impact is for ADCs, DACs and wireless analog/RF functions from 1-10 GHz. There are also many microwave and microelectronics areas where the use of Si/Ge should have a major impact. The major microelectronics areas include:

    ⇒ Linear ADC for radars, telecommunications, medical imaging, instrumentation, etc.
        – Low power (<10-100 mW), 12-16-bits, 100 MSPS
        – High-speed, 6-10 bits, ≥ 10 GSPS - 1000 MSPS
    ⇒ High-resolution, low power delta-sigma ADCs for radar, telecommunications, medical imaging, control, etc.
        – High-speed, 16-18-bits, 100 MSPS
        – High-resolution, 20-24-bits, 10-1 MSPS

    ⇒ High frequency DACs for displays and high definition television (HDTV)

⇒ Digital ICs for
  - Low voltage, high speed, field programmable gate arrays (1-10 GHz)
  - Bipolar/Complementary Metal-Oxide-Semiconductor (BiCMOS) gate arrays, digital signal processors and microprocessors

⇒ Mixed-signal ICs
  - BiCMOS signal processing components
  - Read/write heads, automotive, HDTV, telecommunications, instrumentation, etc.
  - Fiber optic receivers and multiplexers
  - On-chip data conversion and digital signal processing
  - Wireless communication, wireless LANs and portable computing

The major RF/microwave areas include:

⇒ Wireless communications

⇒ MMICs for radars, EW, telecommunications, satellite communications, instrumentation, etc.
  - Highly integrated radar/telecommunications systems for DC to Ku-band (~18GHz)

⇒ Microwave power devices and ICs for solid state active-arrays used in radars, EW, IFF, satellite communication, and cellular base stations

- Circuits with significant performance have been demonstrated using Si/Ge technology. Some of the circuits demonstrated thus far are:

  ⇒ 14-16-bit bandpass ADC (50 MHz BW @ 1GHz)

  ⇒ 10-bit, 3 GSPS DAC

  ⇒ 12-bit, 1 GSPS DAC

  ⇒ 20 Gbit/s fiber optic receiver and decision circuit

SPECIAL TECHNOLOGY AREA REVIEW ON SILICON/GERMANIUM TECHNOLOGY

Technology Overview

The attractiveness of Si/Ge technology derives from the expectation that it can be integrated into existing, cost-effective silicon processes thereby riding the silicon technology curve into the future. In the most mature Si/Ge device, the heterojunction bipolar transistor (HBT), a graded concentration of germanium (Ge) is introduced into the base region. This reduces the band gap of the base material, thereby increasing emitter efficiency and the common-emitter gain (beta). The grading in the Ge concentration also produces a built-in drift field which increases the base transit time, ultimately allowing for gain cutoff frequencies much higher than can be achieved with Si homojunction bipolar transistors. These fundamental advantages enable design tradeoffs that permit significantly improved combinations of device characteristics to be realized. For example, the smaller base band gap increases emitter efficiency and results in higher common-emitter current gain beta. The higher beta in turn allows a tradeoff for a more heavily doped base, thereby decreasing the base resistance. The anticipated end result is better device characteristics that can be used to produce low cost, very low power, low noise, high gain, high efficiency linear amplifiers; high power microwave amplifiers; and low cost, high speed, high resolution, digital-to-analog/analog-to-digital converters (DACs/ADCs). A value- added downstream benefit of Si/Ge occurs from the fact that Si/Ge HBTs can be fully integrated with silicon CMOS on the same chip, further reducing production costs while increasing circuit performance and functionality per IC die.

Materials

The 4.17% room-temperature lattice mismatch between Si and Ge represents a major bandgap engineering challenge, and this alone could be the pacing strategic issue which determines the ultimate success of Si/Ge technology. For device quality material, the thickness of Si/Ge layers epitaxially grown on Si must be carefully controlled to be less than the "critical thickness" for film relaxation. If the critical thickness is exceeded, islanding and 3-D growth occurs at the interface, along with the generation of misfit dislocations which compromise device performance. The critical thickness depends on the Ge content of the layer. In the case of Si/Ge HBTs, Ge content is usually kept below 25% to minimize these defects, resulting in electronic device quality Si/Ge films having suitable thickness for high performance HBTs. However, the lattice mismatch may limit performance in other devices.

Currently, the two most popular techniques for epitaxially growing Ge/Si structures are molecular beam epitaxy (MBE) and various methods of chemical vapor deposition (CVD).

MBE is a physical, surface-controlled growth process that is capable of producing an extremely abrupt interface. Initial attempts to produce Si/Ge by MBE failed because growth temperatures had to be kept above 750° C. It was not until the early 1980s, when growth temperatures could be reduced to 580° C, that smooth, high-quality Si/Ge films were first obtained. Today, MBE processes are usually run at temperatures below 550° C with pressures at about 10^{-10} torr. MBE has been used to grow epitaxial layers for HBTs both on bulk silicon and on TFSOS (Thin Film Silicon on Sapphire). The highest maximum frequency of oscillation (fmax, 90 GHz) reported for Si/Ge HBTs was obtained at Daimler-Benz using MBE. A fundamental advantage of the MBE growth process is the flexibility to alter growth parameters during growth which, in turn, makes this growth technique the choice of most initial device investigations. However, the MBE technique may not translate easily to a manufacturing environment since, at the present time, Si and Si/Ge MBE is restricted to single-wafer growth, and the extension to batch growth processes has not been developed.

There are several types of Si/Ge growth techniques that are batch process compatible and, hence, show early promise of being appropriate for manufacturing: ultra-high-vacuum CVD (UHV/CVD), atmospheric-pressure CVD (APCVD) and reduced-pressure CVD (RPCVD). UHV/CVD, developed by IBM, is a chemical process involving a hot wall reactor and, at present, is the only growth technique reported successful for fabricating integrated circuits on Si/Ge. Growth is normally performed at temperatures below 550°C and pressures below 10^{-3} torr; deposition rates up to about 5 A/min have been achieved at 500°C. The advantages of UHV/CVD are that it has proven itself to be integrable with silicon processing and has produced meaningful, high performance Si/Ge IC results at the 2800 transistor integration level. It uses low temperatures (which permit selective area growth) and it lends itself to batch growth (as many as twenty 200 mm wafers in one batch) processing. The disadvantages of UHV/CVD are that it employs relatively low growth rates and has a limited n-type doping technology. UHV/CVD is now available as a commercial system from Leybold-AG. This commercial system accommodates up to 5 in. wafers but IBM presently has a UHV/CVD system that accommodates 8 in. wafers. IBM asserts that they have had a stable Si/Ge manufacturing process for three years and have achieved yields of 75% on wafers containing 30,000 1.5 μm-by-1.5 μm HBTs. It should also be noted that HBTs made from UHV/CVD material have the highest reported f_t values. Even more importantly, a DAC IC was reported at the 1993 IEDM which contained more than 2800 HBTs. This is the highest level of integration reported using Si/Ge material, and demonstrates that Si/Ge applications are not limited by fundamental material problems. APCVD has been used extensively in the growth of epitaxial Si and has been investigated for Si/Ge growth. Commercial APCVD systems are available (from ASM Epitaxy) for growth on up to 8 in. wafers. To-date, APCVD has not demonstrated high levels of integration for Si/Ge HBT circuits. The advantages of APCVD are that it is a standard technology in the silicon industry, has a high growth rate and has proven n- and p-type doping technology. The disadvantages of the APCVD process are that it requires a high growth temperature (650-725°C), is a single wafer growth process and is difficult to grow on patterned substrates. Some of the APCVD process disadvantages have been alleviated by the reduced pressures in the RPCVD process. A commercial RPCVD system has been used by Motorola to fabricate high performance HBTs with an f_t value of 31 GHz. In RPCVD selective area growth can be obtained with a wide set of growth temperatures and Ge compositions. There are still the disadvantages that RPCVD is a single wafer process and high growth temperatures are required.

More R&D is necessary in the material area before Si/Ge technology will have a significant impact in the RF or digital world. For example, there is no GaAs-like native semi-insulating substrate (Si or Si/Ge) from which to build microstrip or coplanar MMICs with a GaAs approach although SOI on a high resistivity substrate or TFSOS may prove to provide sufficient isolation. Also, it is not completely clear why the IBM UHV/CVD technique works so well for microelectronics (digital) ICs and whether or not the technique can be extended to MMICs which incorporate passive components. But, it is generally agreed that IBM's success is definitely tied in part to their understanding of individual HBT design data that can be used to predict device frequency response. This emphasizes the need for extensive databases of material properties derived from fundamental chemistry/physics and material characterization work. These sources of accurate data will permit the development of accurate design models/simulators necessary to successfully manufacture, with high yield, the devices and circuits being proposed as candidates for using Si/Ge technology.

Film uniformity and reproducibility on large wafers must be improved. In the microelectronics area, work needs to be done to effect low temperature patterned wafer surface preparation and passivation, defect suppression for very large scale integration (VLSI), in-line probes for defect detection, precision chemical/physical characterization, non-conductive substrates and artificial lattice constant substrates. Furthermore, although the results of integrating Si/Ge technology with conventional silicon processing have been promising, higher levels of integration must be demonstrated in order to make it a commercially viable technology. Processing and reproducibility issues in Si/Ge must be investigated more thoroughly. These include dopant diffusion, Schottky barrier technology, oxidation, ohmic contacts, ion implantation/activation and etching.

Devices

At present, HBTs, resonant-tunneling devices (RTDs), field effect transistors (FETs), high electron mobility transistors (HEMTs), and transferred electron devices (TEDs) have been fabricated on Si/Ge. A novel p-channel heterostructure Si/Ge-Si MOSFET (metal oxide semiconductor FET) has been constructed that offers the possibility of permitting the scaling of silicon devices more effectively to dimensions less than 0.1 μm by controlling subthreshold currents with bandgap energy. However, in view of its greater maturity, the HBT is the most likely device technology for near-term demonstration of the commercial and military promise of Si/Ge technology. The key device benefits of Si/Ge technology for HBTs are high thermal conductivity, low base resistance, high carrier drift velocity in the collector, temperature insensitivity of current gain, low 1/f noise and low turn on voltage for low voltage operation.

As discussed above, the HBT offers higher speed and lower power consumption than is obtainable from homojunction bipolar transistor structures. To-date, most high-performance HBTs have been built using GaAs to take advantage of that material's superior speed capability relative to Si. However, there continues to be intense interest in developing higher-speed Si-based HBTs to address markets where GaAs may not prove to be cost effective. This interest area seems appropriate for Si/Ge. Discrete device results have been promising. IBM has demonstrated an f_{max} of 60 GHz with a 0.5x2.5 μm^2 NPN HBT and a ring oscillator delay of 18.9 ps for an ECL circuit. Daimler-Benz has demonstrated an f_{max} of 90 GHz and has projected a near-term goal (desire) of attaining less than 1dB noise figure for a discrete Si/Ge device operating at 20 GHz. Large scale integration must be attained to yield cost-effective products.

In addition to the development of a high-yield processing technology, large scale integration requires the development of better models and design tools for passive circuits on Si substrates. Most circuits realized thus far have been extensions of lower-frequency analog circuits. Implementing transmission lines and reactive components on Si is a relatively new research area, and models developed for semi-insulating GaAs substrates need to be appropriately modified or extended to accurately model Si-based circuits. To-date, promising results have been demonstrated for Si devices fabricated on SOI substrates and on high resistivity Si substrates. Better models should greatly help to improve upon these encouraging results.

There are Si/Ge devices other than HBTs which may have DoD applications. These devices include Si/Ge HEMTs, Si/Ge CMOS circuits and Si/Ge multiple-quantum-well IR detectors. For example, IBM has fabricated a high performance n-type channel HEMT with a 0.5 μm length T-gate that has a peak transconductance of 390 mS/mm. More IBM work has led to a CMOS circuit using 0.25 μm gate length FETs having transconductances of 140 and 230 mS/mm for the p- and n-channel devices, respectively. F_t and F_{max} will be measured shortly. Work at the University of Texas at Austin investigating at MOSFETs with channel lengths less than 0.1μm. However, much of the material for these devices is still in the development stage. For these and other devices, the presence of Ge may not be as compatible with Si device fabrication as is the case for the HBT. Many processing issues must be investigated in order to assess the viability of using Si/Ge in conjunction with other than HBT devices.

The following is a breakout of the work that needs to be done in the Si/Ge device area before either military or commercial products can emerge. First, cost/performance tradeoff ranges for Si/Ge vis a vis silicon and GaAs need to be defined (cost is a complex, marketplace-driven issue) in order to properly focus device research. Although the contention that the introduction of Ge into the base provides useful design latitude seems sound, many of the improved combinations of device parameters have yet to be demonstrated. Second, Si/Ge device models (quantitative models) and simulators (with magnetic and debiasing effects) must be developed and validated with experimental data in order to more accurately predict how physical parameter alterations will affect the device. Third, profile design and optimization of Si/Ge devices needs to be done to enhance device performance. Fourth, there needs to be more research into the potential of Si/Ge for RF power devices. Finally, there must be research to determine the radiation hardness and reliability of Si/Ge devices. At present there is only a small HBT reliability effort in the Air Force. This list is not inclusive but merely intended to highlight the more pressing issues at hand.

Applications Overview

An important question to be addressed with regard to Si/Ge technology is its potential application to military systems: What need does DoD have for this technology? As pointed out earlier in this report, this question must be carefully couched to include the impact of marketplace factors such as cost, time to market, commercial impact and ability to ride the silicon technology curve far into the future. Therefore, both military and commercial potential uses for Si/Ge technology will be presented below with appropriate suggestions for dual-use leverage.

The anticipated major benefit of Si/Ge technology is cost reduction/unit of performance: it must be cheaper than competing technologies. This projected benefit is based upon the assumption that Si/Ge can be made compatible with conventional Si processing and that this compatibility will continue to exist for future circuit designs. Therefore, Si/Ge technology could directly benefit military applications that require high volume production of integrated circuits. These applications would most likely be in the areas of communications, radar and sensors. For example, in the area of communications, Si/Ge technology could be used for high volume items such as data links for computer networks, high speed data converters, optical fiber transmitters/receivers and RF circuitry for portable systems. Si/Ge could play an especially significant role in portable systems if products made from it are cheaper than comparable GaAs parts. Furthermore, it has been pointed out that Si/Ge technology can also be used in any application involving disposable sensors such as for smart munitions or intelligent mines. Si/Ge technology can also be used in vehicle sensors where large numbers of identical sensors are required. Lastly, Si/Ge technology in the form of MMICs and discrete RF sources could be used in radars employing solid state phased array elements and signal processors. Nevertheless, the long-term viability of Si/Ge technology, and its acceptance by DoD, will be largely dependent upon its acceptance in the commercial marketplace.

Because of its potential for low power dissipation, Si/Ge technology could make a significant impact in the communication of voice, video and data, all of which are key to four current Army (CECOM) initiatives: owning the night, digitizing the battlefield, combat identification and owning the spectrum, both offensively and defensively. Moreover, Si/Ge technology could be used to satisfy current DoD initiatives such as in MILSTAR ground terminals and SINCGARS upgrades. There is also the possibility of using Si/Ge technology in the Human Platform 2000 system for helmet mounted FLIRs, combat IFF, precision lightweight GPS Receivers (PLGARs), cellular radio and personal communications. Si/Ge could also be used in the Air Force's Theater Deployed Communications (TDC) for C^4I Systems, which places an emphasis on commercial technology and has requirements for light weight multi-band satellite communication terminals (LMSTs): X/C/Ku-band, wireless LANs and microwave radio communications.

Commercial applications of Si/Ge bear much likeness to their military counterparts. This reinforces the hypothesis that Si/Ge will be a commercial end use technology which can be upgraded to meet military needs for operation under harsh environments. Si/Ge technology could also play a substantial role in the rapidly expanding commercial cellular phone, portable computing, wireless LAN, interactive video and high end microprocessor (workstation) markets. There is also the possibility of using Si/Ge in GPS systems, RF tags, collision avoidance radar and sensors for automobiles. For example, Daimler-Benz is targeting a 24 GHz Si/Ge HBT low noise local oscillator for use as part of the SIMMWIC (silicon monolithic millimeter wave integrated circuit) technology they are developing for velocity measurement in automobiles. SIMMWICs also addresses the automobile collision avoidance/toll collection application areas and makes use of high resistivity silicon substrates to allow integration with monolithic silicon IMPATTs that operate at a frequency of 77 GHz.

Economic Impact

The economic impact of Si/Ge technology could be significant in the some of the previously mentioned markets, especially for wireless communication, portable computing, wireless LAN, displays, HDTV and fiber optic communications. Japanese companies like NEC and Hitachi and European companies like Daimler-Benz and Phillips are working very hard in the area, although IBM is still the clear leader in the field. Currently, NEC has accelerated its effort and is gaining ground. There is a danger that this technology could be lost to Japan if it is not pursued more vigorously by American companies and universities. The US principals are: IBM, Motorola, AT&T, HP, Analog Devices, MA/COM, Q-Dot, Princeton University, University of Minnesota, University of Texas at Austin, and Auburn University. In the case of microwave Si/Ge technology, Japan and Germany may be ahead of IBM. In particular, NEC in Japan has demonstrated a 20 Gbit fiber optic receiver/decision circuit using Si/Ge HBTs fabricated on an SOI substrate that includes a coplanar transmission line. Also, Daimler-Benz in Germany has achieved a HBT f_{max} value of 90 GHz and a f_t value of 101 GHz using self-aligned, mesa isolated devices on a low resistivity substrate. Noise figure was 0.9 dB at 10 GHz with 6.5 dB associated gain. The Daimler-Benz Si/Ge work on high resistivity silicon substrates has been previously mentioned in this report. Other foreign companies developing Si/Ge HBTs include Phillips and Hitachi.

Detailed Findings

Materials

- Ultra High Vacuum-Chemical Vapor Deposition (UHV-CVD) is a production growth technique fully compatible with silicon processing. It lacks a complete n-type doping process and has low growth rate.
- Si/Ge Molecular Beam Epitaxy (MBE) capability is currently limited and restricted to growth on single wafers. It is not compatible with a silicon-like processing line.
- Reduced pressure UHV-CVD is commercially available (production-ready silicon epi), is silicon process compatible, but is limited to single wafers.

Devices

- Si/Ge is viewed primarily as a commercial end use technology with commercial off-the shelf (COTS) and military specification (MILSPEC) potential similar to that of silicon microcircuits.

- Si/Ge heterojunction bipolar transistor (HBT) technology is judged to be ready for product exploitation in merchant markets where GaAs may not prove to be cost effective.

- For DoD applications, non-HBT Si/Ge devices (HEMTs, CMOSFETs, etc.) may be important in the future, but are now in the basic research stage.

- Si/Ge device models and simulators are not adequate, thereby significantly limiting profile design and device optimization.

- No radiation hardness and reliability data base exists for Si/Ge devices and ICs.

Circuits

- Key circuits judged appropriate for exploitation in Si/Ge are analog-to-digital converters (ADCs), digital-to-analog converters (DACs), high speed gate arrays, fiber optic receivers/multiplexers, digital (BiCMOS) signal processors and RF/microwave gain blocks/power amplifiers.

- The most advanced Si/Ge circuits are a 12 bit, 1 GSPS DAC and a 20 GbPS optical receiver IC. The DAC sets a new standard of performance for all types of DACS.

- Lack of a sufficiently insulating substrate or appropriate SOI technology limits the realization of system level RF/microwave chip solutions that depend on integrating passive components with active devices.

- The far-term promise of Si/Ge circuits is believed to be for BiCMOS ICs and RF ICs fabricated on SOI.

Manufacturing Technology

- Si/Ge HBT technology may offer attractive cost alternatives to other technologies. However, there is still a valid concern that any <u>non-standard</u> silicon MOSFET technology could be too expensive for anything except specialty applications.

- A well defined manufacturing toolset for Si/Ge devices/ICs is emerging, but its accessibility is limited to one or two companies.

- Si/Ge infrastructure tools are limited and this, in itself, restricts the current marketplace success of Si/Ge HBTs. Currently, Si/Ge HBT design relies heavily upon software available for silicon and GaAs.

- A commercial market for Si/Ge is necessary to allow cost effective production of the volumes of parts required by the DoD.

- The Air Force and IBM are working together to establish a QML for the IBM Si/Ge HBT line.

Funding

- The Navy is the principal DoD investor in Si/Ge technology at approximately $2M/YR in FY94. Navy money is split 50/50 between 6.1 and 6.2 activities. Si/Ge microwave power HBTs and high speed ADCs are being pursued under 6.2 funds.
- The Air Force is looking at Si/Ge reliability while ARPA has a SBIR effort investigating advanced Si/Ge circuits/reliability.
- IBM has made substantial investments to-date on Si/Ge technology
- Si/Ge is competing with many other technologies (silicon, GaAs, InP, SiC and etc.) for a share of the DoD retrofit and possible new system markets of the future. Winning technologies for rapid insertion will require domestic merchant market viability: the product needs to be on the shelf or amenable to a rapid prototyping process.
- The DoD is not expected to be able to expand its out-year investment in Si/Ge significantly above that of FY94 dollars. Any additional Si/Ge out-year funding should be directed toward Si/Ge device/circuit and infrastructure activities that support a military need that is not being addressed by the commercial world.

Detailed Recommendations

Materials

- DoD should encourage (for example, through CRADAs) high resistivity silicon substrate research to allow incorporation of passive microstrip components into RF circuits.
- Basic research needs to be done to develop selective growth techniques for Si/Ge, for minimizing deleterious effects of lattice mismatch between Si and Si/Ge (to include models, simulations and validation databases) and to determine basic Si/Ge growth mechanisms.
- DoD should encourage motivation of a maturing Si/Ge growth process that is amenable to patterning, production and doping control and is fully compatible with present and projected silicon technology processes (requires focus on UHV-CVD or reduced pressure UHV-CVD).

Devices

- DoD could obtain a valuable return on investment (ROI) by investing in Si/Ge devices and ICs for high volume DoD need areas (ADC, DAC, wireless) and also for lower volume needs such as HBT power devices.
- DoD should invest carefully in basic research areas such as RF passive element models, device design models, physics of failure, device simulators and process science.
- DoD should consider an out-year investment in non-HBT devices considered critical for military applications.
- DoD should assess the potential of Si/Ge devices for satisfactory performance in harsh radiation environments and, if warranted, develop models and processes that lead to improved radiation hardness.

Circuits

- DoD should carefully consider establishing a SOI circuit technology infrastructure base in anticipation of the far-term requirements for of Si/Ge circuits.
- DoD system developers need to consider methods for fabricating passive on-chip components necessary to provide complete system approaches.
- It makes near-term economic (ROI) sense for DoD to invest in high speed Si/Ge ADCs and DACs for military applications.
- DoD should keep abreast of fiber optic technology developments which can be effectively integrated with Si/Ge technology.

Manufacturing Technology

- Cost/performance tradeoff ranges vis-a-vis silicon and GaAs need to be carefully defined and tested through a demonstration project centered on producing a product(s) with a given set of application driven performance specifications. Any technology that solves the application problem is then acceptable.
- DoD should encourage the extension of manufacturing tools to include applicability to Si/Ge using, for example, TRPs (or possibly Sematech), this would insure that these production tools are available to everyone.
- The compatibility of Si/Ge processing with Si processing should be demonstrated for large or complex circuits.

- DoD should carefully invest in key infrastructure tools such as processing/circuit models and simulators, possibly at universities.

Funding

- Near-term DoD funding needs to be focused on 1) military high payoff areas such as ADCs, DACs, microwave power transistors and 2) severely needed infrastructure development areas such as database acquisition for design tool validation and developing epitaxial growth processes capable of "riding" the silicon technology curve.

- Si/Ge progress needs to be monitored carefully by DoD advisory groups to take advantage of technology advances to realize systems savings for DoD.

- DoD far-term investment in Si/Ge will depend on the ability of Si/Ge to keep pace with the development and manufacturing of silicon components. This will require a high degree of manufacturing compatibility between Si/Ge and silicon processes. The implementation of this manufacturing compatibility should be funded mostly by the commercial sector.

ADDENDUM: Mini STAR on Si/Ge Devices

Because progress in Si/Ge technology is moving forward with ever increasing speed and generating growing interest, it represents a "moving target" which should be periodically revisited. On 14 June, 1995, a mini STAR for Si/Ge was conducted by Working Group A (WGA) to review the earlier findings and to determine whether or not the Department of Defense (DoD) should change its investment policy for that technology. At the 1994 International Electron Devices Meeting (IEDM) conference in San Francisco, some papers were given which strongly suggested that SiGe might play a key role in the emerging rf market which promises to be huge by any measure. How would such a development impact gallium arsenide (GaAs) and related compounds? Also, there is growing evidence that 0.25μm complementary metal oxide semiconductor (CMOS) technology has much to offer at frequencies below X-band. Certainly the possibility of monolithic integration would make such an approach very attractive. These are very exciting times in terms of progress and potential changes in our traditional thinking. How would the emergence of such potentially lower cost devices impact the availability of GaAs and related compounds? In particular, how might this situation impact industry's ability to support DoD's future requirements?

The preceding report has detailed many of the inherent advantages of SiGe and consequently this information will not be repeated other than to say that the evidence today supporting SiGe performance is exceeding the expectations of only a year ago.

The three most basic advantages of SiGe over Si are as follows:

1. The reduction in base transit time which increases f_T and f_{max}.

2. The increase in collector current density which yields higher current gain with low base resistance.

3. The increase in Early voltage for a given cutoff frequency.

If all of the SiGe parameters are optimized for a particular application, the overall speed advantage compared to Si bipolar junction transistors (BJTs) is on the order of 50%. Although this figure is below the most optimistic projections, it is still quite impressive. More importantly, it makes possible many applications which address very substantial commercial markets.

All of the speakers and other contributors at the mini-STAR review stated quite emphatically that the manufacturing aspects of this new technology will determine its success in the marketplace. If the devices and circuits require special equipment and complicated processing steps compared to high quality silicon BJTs, then the general acceptance probably will not materialize. Or, if the yields and uniformity are questionable, other approaches will clearly prevail. Recognizing these universal truths, IBM has devoted considerable resources in the acquisition of manufacturing data on 8 inch wafers processed on a manufacturing line--not in a development laboratory. To-date, the data is very impressive indeed, indicating a very mature and stable manufacturing process. If there are no big surprises in the near future, it would appear that a very big hurdle has been overcome. Naturally, considerable work remains to be done, but this effort is straightforward and does not entail high risks.

The real and present driver for this technology is the explosive wireless communication market including cellular phones, cordless phones, pagers, personal digital assistants (PDAs), wireless local area networks (LANs), and many other potentially big businesses. There are three criteria which must be satisfied to prevail in this market: low cost, low cost, and low cost. The speakers were unanimous in this judgment. They emphasized this point by citing the example of cellular phones which became the success story of the century once they became affordable. This particular market is poised for another explosion with the introduction of digital technology which will rapidly replace analog phones with the steady decrease in price. As potentially the lowest cost technology capable of addressing most of these markets, Si/Ge could be the device of choice for most wireless applications.

System and circuit architecture are becoming ever more important for wireless applications because of the crowded spectrum, forcing digital implementations along with intensive signal processing. Also, battery considerations such as size, weight, life and reliability severely limit the allowable power drain of the system. Here again, the digital approach permits some innovations which can result in significant power savings. Power added efficiency (PAE) for the output amplifier is just one consideration. The entire power budget is the key to solving the battery problem.

The battery is another major cost driver. Battery considerations such as size, weight, lifetime and reliability severely limit the allowable power drain of the system. Low voltage operation is key to achieving low-cost, small-volume battery solutions. Si/Ge has demonstrated the capability to work satisfactorily at three volts and below.

Architecture also impacts packaging considerations. The bottom line cost is very sensitive to the number of chips required and the type of interconnects required. The cost of assembly is a major determinant in this cost picture. For this reason, the goal of a single chip implementation will always be a high priority objective.

For many of the wireless applications now under study, SiGe BJTs offer attractive performance advantages, but the jury is still out regarding a final choice. In some systems a combination of technologies might well serve the near term needs with the more monolithic approach taking over for the next generation. In any event, cost will always be a major part of the equation. For this reason, GaAs and related compound semiconductors may be at a distinct disadvantage in holding on to the wireless market opportunities. This is true even though, in some instances, GaAs gives superior performance with respect to power output and PAE. If the wireless market does not provide GaAs with a good manufacturing base, the future for that technology will become very clouded and the end result may be that the military will remain the primary customer. Such a trend presents some long range problems which must be addressed in future budgets.

In addition to the rf market, SiGe BJTs offer excellent characteristics for the high speed, mixed analog and digital market, such as analog-to-digital converters (ADCs) and digital- to-analog converters (DACs) and other high speed random logic circuits. Already IBM and Analog Devices, Inc. have demonstrated some very high speed DACs with 12 bit resolution. However, circuits of this sort comprise only a niche market and cannot supply a large base for maturing the technology.

The automotive market for collision warning, collision avoidance, and intelligent transportation systems is just in the demonstration phase. SiGe looks very promising for some of these applications but it is too early to predict which technologies are going to be winners. However, it would appear that GaAs is not looked upon with favor because of the much higher cost estimates. The quantities of circuits required are very substantial, but the cost goals are very ambitious indeed. The primary considerations are functionality and reliability. The power requirements are easily met because of the automotive power system already in place. However, the environmental considerations such as temperature and physical abuse create some challenging problems. Because of the very sharp antenna patterns required to discriminate against false targets, the frequency is generally above X-band and as high as 76 GHz. GaAs devices, particularly psuedomorphic high electron mobility transistor (PHEMT) structures, may hold an insurmountable performance advantage over Si/Ge at these higher frequencies. The efficiency is not at all critical since the prime power is not limited. Initially, the various systems will only be offered as an option on the more expensive cars and trucks. If the buying public is happy with the performance, then the numbers could grow substantially. However, this market should not be viewed as a big winner until the systems have been thoroughly evaluated by the car owners.

At this stage in the evolution of SiGe device and circuit technology, no compelling reason has emerged that would significantly change the current DoD investment plan nor is there justification to augment any specific development effort in SiGe. The progress in the development of SiGe technology is very positive and needs to be carefully monitored by the DoD. Opportunities to apply this technology to military needs should not be overlooked. Also, the Services need to recognize that for ultra-high-frequency (UHF) and microwave frequencies below X-band, GaAs, Si, and SiGe are all strong candidates. The final selection will depend upon the maturity of the chosen technology and its fit to the particular requirements. This multiplicity of choices significantly challenges the commonly held belief that GaAs would be the mainstream microwave solid state technology for all military applications. In reality, some of this market will be shared by other technologies such as SiGe, 0.25μm CMOS, and possibly even some of the newer compounds such as silicon carbide/gallium nitride (SiC/GaN). This could severely limit the economy of scale achieved by GaAs and, therefore, would skew this technology to favor highly specialized products. It is premature to predict the outcome of this very dynamic race, but it is prudent for the DoD to continually assess this situation and to adjust its investment plan accordingly.