



**AFRL-RY-WP-TM-2012-0228**

**SCIENTIFIC AND TECHNOLOGICAL ACHIEVEMENTS,  
1946-2011, OF THE AFRL ELECTROMAGNETICS  
TECHNOLOGY DIVISION (AFRL/RYP) AND ITS  
PROGENITORS**

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**Electromagnetics Technology Division  
Sensors Directorate**

**JULY 2012  
Final Report**

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**Scientific & Technological Achievements, 1946-2011,  
of the AFRL Electromagnetics Technology Division (AFRL/RYPH)  
and its Progenitors  
by  
Michael N. Alexander  
Division Technical Advisor (2002 - 2011)**

## **1.0 Introduction**

The genesis of this report was a call that HQ Air Force Materiel Command (AFMC) made in late 2010 for lists of significant technology achievements and technology transitions. Mr. Raymond Rang, the AFRL Sensors Directorate (AFRL/RYPH) historian, forwarded AFMC's request to RYPH's Divisions. I responded for the Electromagnetics Technology Division (AFRL/RYPH).

Ray could use no more than a few citations of each Division's achievements and transitions; my list was longer. That circumstance, together with the fact that RYPH would soon be relocated, per the 2005 BRAC (from Hanscom AFB, MA, to Wright Patterson AFB, OH), stimulated me to create a list that encompassed the entire period 1946-2010 -- from RYPH's origin (under a different name and parent organization) shortly after World War II through its penultimate year at Hanscom AFB. Further impetus now comes from news that in August 2012 or shortly thereafter, RYPH's Branches will be absorbed into other Divisions of the Sensors Directorate.

Not long after I expanded the lists, I realized that their constituent topic statements were too cryptic to be understood by most non-specialists. Therefore, with Ray's encouragement, I proceeded to develop short descriptions that fleshed out achievements on the list.

The body of this report, therefore, lists and briefly describes RYPH's most significant research and technology achievements, including associated technology transfers and transitions. Some of them were seminal. I believe most others were enduring contributions, mileposts within the evolutions of major technologies. Of necessity, many other important, RYPH contributions could not be included. To some extent, the list of patents in the Appendix addresses this shortcoming (preparing a list of refereed publications was too daunting, since good records were not available).

In 2011, when the Hanscom AFB Research Site and its "remote" sites in Ipswich and Sudbury, MA were shut down, the Electromagnetics Division (AFRL/RYPH) was authorized approximately 80 positions (down from approximately 120 in 2000), plus an approximately equal number of on-site contract researchers and support staff. An overwhelming fraction of the staff held advanced degrees, most of them doctorates. RYPH was composed of four branches -- the Antenna Technology Branch (AFRL/RYPHA), the Optoelectronics Technology Branch (AFRL/RYPHC), the Electromagnetic Scattering and Phenomenology Branch (AFRL/RYPHE), and the Infrared Sensor Technology Branch (AFRL/RYPHI). There had been an Electromagnetic Materials

Branch (AFRL/RYHX), but it was disestablished around 2002, and its S&Es and physical and assets were distributed among RYHA, RYHC, and RYHI. In many cases this has made it difficult to assign achievements to specific branches; often, achievements are credited simply to the final name or office symbol of the Division, AFRL/RYH.

The names of these branches suggests the scope and diversity of RYH's research and technology. Most of RYH's activities were in basic research and "early" applied research (DoD categories 6.1 and 6.2). However, as will be clear from the Achievements in this report, RYH sometimes engaged in technology development activities. There were copious technology transfers and transitions, and some of the technologies were explicitly incorporated into operational equipment.

I know of few published accounts of RYH contributions. Reports like Ruth Liebowitz's chronology of the Air Force Cambridge Research Laboratory/Center ("Chronology: From the Cambridge Field Station to the Air Force Geophysics Laboratory. 1945-1985," [AFGL-TR-85-0201 (6 September 1985), [www.dtic.mil/cgi/bin/GetTRDoc?AD=ADA164501](http://www.dtic.mil/cgi/bin/GetTRDoc?AD=ADA164501); also available as a Google Book]) -- to which RYH belonged for many years -- emphasize its geophysics and space activities. Reports by the Rome Air Development Center, which absorbed RYH around 1975, and by RADC's lineal successor, Rome Laboratory, almost always attributed successes to the entire organization rather than to its component parts, much less individual researchers and engineers. Such generalized attributions prevented me from documenting some of RYH's contributions -- in particular, contributions to the substantial R&D activity in over-the-horizon (OTH) radar research after 1946. (RYH became part of the Air Force Research Laboratory's Sensors Directorate -- AFRL/RY -- when AFRL was formed at the beginning of 1997.)

As noted above, the Air Force seems to attribute achievements only to organizations -- but in my opinion such generalized attribution is like saying Cambridge University, not Watson and Crick, deciphered the double helix structure of DNA. Consequently, I have endeavored to attribute credit explicitly to individuals and groups, so long as it didn't render the text insufferably ponderous and complex. The names of many individuals do appear, however, in references that accompany descriptions of the achievements and also in the list of patents; even then, it was not possible to cite every individual I knew to have played a part in the accomplishments.

This report assigns years or time intervals to its achievement items. The assignments should mostly be regarded as nominal. A science and technology achievement often arises, matures, and blossoms during more than a single year, especially when the achievement spans basic research, applied research, and/or technology transfers/transitions. Even where time intervals in this report are indicated, the "start" and "completion" years should not be viewed as precise demarcations.

I have rigorously distinguished between achievements of RYH scientists and engineers (S&Es) themselves and achievements that resulted from R&D contracts managed by RYH S&Es but executed by non-government researchers. The definition of "in-house" employed here includes only research collaborations in which RYH S&Es played significant or leading roles (collaborations in which RYH S&Es could not have been "courtesy" co-authors of publications,

for example). On-site contract researchers are considered, here, to be “in-house” researchers; they were part of the family.

In this report, references that accompany descriptions of the achievements were chosen, in part, to provide evidence for who deserved credit. Whenever it was possible, I also included references that I hope can be understood by interested non-specialists – for example, articles in *Scientific American*, *Physics Today*, and trade magazines like *Microwave Journal*. In part, these references serve the function of countering the much-too-common suspicions that, as federal government employees, RYH’s S&Es were merely contract jockeys who rode on the backs of private-sector contractors and appropriated credit for their work. For essentially the same reason, this report consciously cites national and international honors that RYH researchers received for their work.

## 2.0 Acknowledgements

I am deeply indebted to Ray Rang for his encouragement, support, editorial help, advice, and patience throughout the entire time this report took form. Mr. Charles Tsacoyeanes contributed excellent first drafts of many optoelectronic device sections. His trenchant critiques were a wake-up call that immeasurably improved the understandability of technology descriptions and their significances. Dr. Freeman Shepherd contributed passages on infrared imaging sciences; he also rewrote infrared technology descriptions and corrected other errors in my drafts. Dr. Robert Mailloux contributed summaries of advances in phased array antenna technologies. Drs. Robert Shore and Arthur Yaghjian supplied fine summaries of their pioneering research on Incremental Length Diffraction Coefficients and on metamaterials. Dr. William Stevens and Mr. Richard Marr furnished an excellent summary of contributions to measurement of bistatic radar cross sections. Other colleagues whom I thank for important contributions and insights before and during creation of this report are (in reverse alphabetical order): Dr. Charles Woods, Dr. David Weyburne, Mr. Bertus Weijers, Mr. John Turtle, Dr. Boris Tomasic, Dr. Qing Sun-Paduano, Dr. Hans Steyskal, Dr. Richard Soref, Dr. Leonid Perlovsky, Mr. Paul Pellegrini, Mr. Michael Noyola, Dr. Steven Mittleman, Dr. Robert McGahan, Dr. Candace Lynch, Mr. Joseph Lorenzo, Dr. Kristopher Kim, Dr. Jed Khoury, Dr. William Ewing, Dr. John Derov, Dr. Paul Carr, Dr. David Bliss, and Dr. Edward Altshuler. Throughout my years in AFRL/RYH, I learned from all of them. Their writeups, critiques, and advice strengthened this report. I, of course, am responsible for residual errors and shortcomings.

It would be impossible for me to name and acknowledge all the external organizations that sponsored RYH research. Nonetheless, the Air Force Office of Scientific Research (AFOSR) deserves special acknowledgement and gratitude for their support of RYH’s programs – never uncritical, yet continuing through decades. AFOSR officials and program managers who, in my personal experience, deserve special mention are Drs. Horst Wittman, Gerald Witt, Howard Schlossberg, Gernot Pomrenke, and Arje Nachman. AFOSR as an organization richly deserves gratitude from the Air Force and DoD for their stalwart support, advocacy, and defense of high-quality in-house (as well as extramural) basic research, even throughout intervals when long-range and basic research were woefully out of favor.

## 3.0 The Achievements

### 3.1 Genesis of Over-the-Horizon (OTH) Radar (1946)

#### IN-HOUSE RESEARCH ACHIEVEMENT

Over the horizon (OTH) radar, as its name implies, was conceived and developed to detect and track targets beyond the horizon. Conventional radars, by contrast, can detect targets only within line-of-sight. In 1946, scientists at the Army Air Forces' (ancestor of the USAF) Cambridge Field Station (earliest progenitor of RYH) invented a radar concept in which radar beams were reflected off the ionosphere to the earth's surface, then back to the ionosphere, and so on.

During the late 1940s the Army Air Forces' Watson Laboratories used such ionospheric "propagation paths" to send signals between Boston, MA and Puerto Rico, and between Boston and the White Sands, NM, Proving Grounds (The Army Signal Corps transferred Watson Laboratories to the Army Air Forces in 1945). A critical observation that enabled OTH was Doppler shifts (changes in the frequency of the radar beam caused by motion of the targets) detected in the returns of the laboratory's radar ionospheric propagation during V-2 rocket launches at White Sands. The observation eventually led to the effort known as Project 440L.

Over-the-Horizon Forward Scatter Radar, or 440-L radar, was developed during the 1960s to detect missile launches from Chinese or Soviet territory. 440-L was a series of high frequency radio transmitters and receivers on either side of the Sino-Soviet landmass that produced continuous signals that bounced between the ionosphere and the surface of the earth until it reached the receiving stations. Disturbances in the pattern indicated that (intercontinental) missiles were penetrating the ionosphere.

#### References:

Thomas W. Thompson, *The Fifty-Year Role of the United States Air Force in Advancing Information Technology – A History of the Rome, New York Ground Electronics Laboratory* (Edwin Mellen Press, 2004), p.35

Ruth P. Liebowitz, "Chronology: From the Cambridge Field Station to the Air Force Geophysics Laboratory, 1945-1985," AFGL-TR-85-0201 (6 September 1985)

<http://www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB7/nsaebb7.htm> ; see discussion of Document 12 in this reference).

## 3.2 First Modem to Operate Over Telephone Lines (1949)

### IN-HOUSE RESEARCH ACHIEVEMENT

The first modem to transmit information over telephone lines was invented by an Air Force Cambridge Research Center (AFCRC) group, led by John Harrington, which worked on what was then called Digital Radar Relay. Their objective was to transmit data from an early-warning radar at L.G. Hanscom Field (now Hanscom AFB, MA) to a site in Cambridge, MA, that had been part of the MIT Radiation Laboratory. Harrington's group first pursued microwave relay transmission, but decided it was unsatisfactory. Then, realizing that telephone lines were inexpensive and becoming ubiquitous, the group invented and used what is now known as the modem ("modulate-demodulate").

AFCRC's telephone-based modem technology became available just as MIT Lincoln Laboratory began work on the Air Force's SAGE (Semi-Automatic Ground Environment) system. SAGE would eventually track all aircraft within the continental US, making it possible to alert air defense units in case any of the aircraft might be Soviet nuclear bombers. SAGE was based on a network of radars; the modem, invented almost next door to Lincoln Lab, was immediately incorporated as a critical element of that network. Harrington's group, in fact, joined the SAGE program at Lincoln Lab.

#### References:

<http://mail.computerhistory.org/pipermail/inforoots/2009-March/002068.html> (downloaded August 2011)

<http://www.ll.mit.edu/about/History/origins.html> (downloaded August 2011)

J. V. Harrington, "Radar Data Transmission," *Annals of the History of Computing* 5 (Oct 1983) 370 ( <http://ieeexplore.ieee.org/stamp.jsp?arnumber=04640772>)

## 3.3 Microwave Printed Circuit (stripline) (1951)

### IN-HOUSE RESEARCH ACHIEVEMENT

Before Robert Barrett's invention of the microwave printed circuit/stripline, and the almost contemporaneous invention of microstrip, microwave transmission circuitry was dominated by bulky, heavy waveguide technology. Barrett realized that a planar equivalent of coaxial cable could be created by, in effect, flattening the center conductor and replacing the outer conductor with a pair of ground planes, sandwiching the center conductor between the outer conductors. Microwave printed circuits were therefore planar technologies that could be inexpensively implemented on what people now know as printed circuit boards. A variety of microwave components could be fabricated in this way.

Use of stripline has become pervasive throughout microwave and antenna circuits. Although important applications still require waveguides, it is hard to imagine the compact microwave and antenna circuitry of cellular telephones being implemented without Barrett's invention.

Mr. Barrett received the 1992 IEEE [Microwave] Pioneer Award. The award citation reads: "For pioneering the development of the strip transmission line. ... The impact of stripline technology on our industry [the microwave industry] is obvious and needs no further amplification."

#### References:

R. M. Barrett, "Microwave Printed Circuits – A Historical Survey, " IRE Transactions on Microwave Theory and Techniques, MTT-3 (Mar 1955) 1.

R. M. Barrett, IEEE Transactions on Microwave Theory and Techniques 32 (Sept 1984) 983

[http://www.mtt.org/images/files/AWARDS\\_media/Pioneer\\_Awards/1992\\_Barrett.pdf](http://www.mtt.org/images/files/AWARDS_media/Pioneer_Awards/1992_Barrett.pdf)  
(downloaded August 2011)

Leo G. Maloratsky, "Reviewing the Basics Of Microstrip Lines," Microwaves & RF, March 2000, p. 79

Constantine A. Balanis, *Antenna Theory*, 3<sup>rd</sup> edition, John Wiley (2005), Chapter 14 ("Microstrip Antennas")

### **3.4 Antenna Design for Arecibo Radio Telescope (1959-1961)**

#### **IN-HOUSE ACHIEVEMENT**

The Arecibo Observatory is the largest single-aperture telescope in the world, 305 meters (1000 feet) in diameter. To achieve a stable structure, the reflector was excavated from the side of a mountain in Puerto Rico. The Cornell University scientists who proposed the pioneering telescope originally envisioned a parabolic reflector.

RYH antenna experts were invited to review the proposed design, and recognized that it would not permit beam scanning other than that provided by the earth's rotation. Based on studies of spherical reflector antennas they had published in the 1950s, the RYH scientists (R.C.Spencer, C J. Sletten and J. E. Walsh) recommended that the reflector shape be changed from parabolic to spherical. Together with a moveable line feed designed by the RYH team, this made it possible to steer the telescope's radio beam over +/- 2 degrees, and also to correct for spherical aberrations. In addition, the RYH team served as manager and technical supervisor during construction of the radio telescope.

Measurements at the Arecibo telescope have resulted in a host of important astronomical discoveries. Reflecting its importance, it is listed in the National Register of Historic Places; in 2001, it was named an IEEE Milestone.

#### References:

[http://en.wikipedia.org/wiki/Arecibo\\_Observatory](http://en.wikipedia.org/wiki/Arecibo_Observatory) (downloaded August 2011)

Andrew J. Butrica, *To See the Unseen: A History of Planetary Radar Astronomy*, NASA History Office, Washington, D.C. (1996), Chapt. 4. Online version: <http://history.nasa.gov/SP-4218/ch4.htm> (downloaded 6/16/2011)

“History and Progress of AFCRL, January 1961-June 1962,” Technical Report AFCRL-62-714 (October 1962)

### **3.5 Rotman Microwave Antenna Lens (1963)**

#### IN-HOUSE RESEARCH ACHIEVEMENT

The Rotman Lens, a staple of microwave and antenna engineering, was invented by Walter Rotman for communications and radar system beamforming. It is an electrical lens that, together with an array antenna, can produce multiple orthogonal beams across a wide angular range with low phase error, making it possible to see several targets at once. Because of its multi-beam and true-time-delay characteristics, Rotman Lens designs have recently been considered for multifunctional antenna applications (e.g., Synthetic Aperture Radar, Electronic Warfare, and Non-Cooperative Target Identification). Moreover, the Rotman Lens has the advantage of monolithic construction, ease of manufacture, low cost, and light weight.

Walter Rotman was awarded the IEEE’s 2005 John Kraus Antenna Award for inventing this unique lens antenna. In 1980 he received the USAF Decoration for Exceptional Civilian Service, and in 1984 he was awarded the IEEE Centennial Medal.

#### References:

W. Rotman, US Patent 3,170,155 (February 18, 1965)

W. Rotman and R. F. Turner, “Wide-Angle Microwave Lens for Line Source Applications,” *IEEE Trans. on Antennas and Propagation* 11 (1963) 623-632

A. C. Schell, “2005 John Kraus Antenna Award – Walter Rotman,” *IEEE Antennas and Propagation Magazine* 47 (April 2005) 114

J. G. Worms, P. Knott, and D. Nuessler, "The experimental System PALES: Signal Separation with a Multibeam-System Based on a Rotman Lens," IEEE Antennas and Propagation Magazine 49 (June 2007) 95—107.

R. L. Haupt, *Antenna Arrays. A Computational Approach*, J.W. Wiley (2010), pp. 432-438

### **3.6 Limited Scan Phased Array Antenna Technologies (1973+)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

A long-standing and continuing antenna requirement has been the need to provide rapid electronic scanning over small angular sectors, on the order of +/- 10 degrees or less. Some of these applications can be met by scanning reflectors or lenses mechanically by means of sub-reflector or feed motion. Systems requiring this capability include Ground-Based Precision Approach Radars and Space-Based Radar.

Since arrays for wide angle scanning require a large number of elements and therefore incur high cost, there is a need for techniques that make use of the reduced scan sector to reduce the number of array controls. Since the 1970s RYH contributed a growing number of advances in this technology, beginning with the use of small arrays at the focal region of a reflecting optical system and progressing through developments of a special array architecture called "overlapped subarrays" that can use fewer array elements and yet not suffer sidelobe or gain penalties. Many of these techniques have since been incorporated into satellite and ground based systems

Dr. Robert Mailloux received the IEEE Harry Diamond Award and the IEEE Third Millenium Medal for his contributions to this and other antenna research. He is an IEEE Fellow and an AFRL Fellow.

#### References:

R.J. Mailloux and G.R. Forbes, "An Array Technique with Grating Lobe Suppression for Limited-Scan Applications," IEEE Transactions on Antennas and Propagation, AP-21, (Sep 1973), 596-602

R.J. Mailloux and P. Blacksmith, "Array and Reflector Techniques for Airport Precision Approach Radars," Microwave Journal, 17 (Oct 1974) 35-38

R.J. Mailloux, L. Zahn, A. Martinez and G. Forbes, "Grating Lobe Control in Limited Scan Arrays," IEEE Transactions on Antennas and Propagation AP-27 (Jan. 1979) 79-85

*Phased Array Antenna Handbook*, Second Edition (2005), by R.J. Mailloux, Artech House, (first edition, 1994), Chapter 8, "Special array feeds for limited-field-of-view and wide band arrays"

### 3.7 Staring infrared (IR) Focal Plane Array (FPA) Technology (1975+)

#### IN-HOUSE RESEARCH ACHIEVEMENT

The staring array concept was a truly seminal advance in infrared imaging technology. FPAs are used in a plethora of ISR and other imaging applications. Staring IRFPAs are similar to the “sensors” used in modern digital still-cameras and video cameras at visible wavelengths in that both record images from arrays of detectors:

AFRL/RYHI’s FPAs were arrays of platinum silicide (PtSi) Schottky diodes fabricated on p-type silicon wafers. Their PtSi program began as a basic research investigation of “internal photoemission” in semiconductors, yielding individual detectors. This work on individual detectors evolved into R&D on arrays of detectors and on staring detector systems, and it spawned related basic and applied research efforts.

A revolutionary infrared imaging technology grew out of this effort. Scanning systems, which were the state of the art in IR imaging technology, had very low signal collection efficiencies, typically less than 0.1 percent, because of their short dwell times on any part of the observed scene. FPAs, on the other hand, image the entire scene all the time and also eliminate the need for moving optics.

Use of silicon technology conferred additional advantages.

- Detectors and read-out electronics could be integrated on the same semiconductor wafer.
- A highly developed integrated circuit (IC) industrial base could be leveraged – and it was.
- By inviting domestic IC producers into its laboratories and teaching them PtSi technology and processing, RYHI created manufacturer acceptance of the technology and facilitated technology transitions to AF operations.
- An integral part of RYHI’s development approach was to specify device processing technologies that were a couple of generations behind the industry’s IC state of the art. This guaranteed unprecedented pixel-to-pixel uniformity (hence, unprecedentedly low “pattern noise”), rock-solid reliability, and high manufacturing yield -- all without compromising performance. PtSi arrays containing hundreds of thousands of pixels were manufactured years before comparatively large arrays became available for other kinds of IR imaging sensors.

Also see entries, below, for Histogram Projection Algorithm (1988) and Platinum Silicide Infrared Cameras (1990+).

#### References:

S. A. Roosild, F. D. Shepherd, Jr., A. C. Yang, and W. Shedd, U.S. Patent 3,902,066 (Aug 26, 1975), “Schottky Barrier Infrared Detector Arrays with Charge Coupled Device Readout”

F. D. Shepherd and A. C. Yang, "Silicon Schottky Retinas for Infrared Imaging," International Electron Devices Meeting Tech. Digest, pp. 310-313, Dec. 1973.

F. D. Shepherd, A. C. Yang, S. A. Roosild, J. H. Bloom, B. R. Capone, C. E. Ludington and R. W. Taylor, "Silicon Schottky Barrier Monolithic IRTV Focal Planes," Advances in Electronics and Electron Physics, Volume 40B, Sixth Symposium on Photo-electronic Image Devices (Sept 1974), pp. 981-992, (Publication delayed until 1976 by printers strike in U.K.)

F. D. Shepherd, Jr. and S. A. Roosild, U.S. Patent No. 4,005,327 (25 Jan 1977), "Low Beam Velocity Retina for Schottky Infrared Vidicons"

[http://www.nano.gov/html/research/Achievements\\_pdf/05-Electronics/NanolayerMidwaveInfraredDetectors-Cameras-AFRL.pdf](http://www.nano.gov/html/research/Achievements_pdf/05-Electronics/NanolayerMidwaveInfraredDetectors-Cameras-AFRL.pdf)

J. Silverman, J. Mooney, & F. Shepherd, "Infrared video cameras," *Scientific American*, March 1992, pp. 78-83

Numerous private communications, over several years, with Dr. Freeman Shepherd and Mr. Paul Pellegrini (AFRL/RHYI)

### **3.8 New Surface Acoustic Wave (SAW) Cut for Reduced-Spurious-Signal Delay Line (1976)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

Surface acoustic wave (SAW) devices utilize ultrasonic surface waves on a piezoelectric crystal. The crystalline deformation from the ultrasonic wave creates an oscillating voltage that can be detected electronically. Because the propagation path is on the crystalline surface, it is accessible for detection; devices utilizing SAW crystals have been widely used in microwave and radar technology for pulse shaping (e.g., creating chirp signals) and for filters.

RYH scientists investigating ultrasonic delay lines discovered a new "cut" (orientation) of lithium tantalate crystals that minimized diffraction spreading, minimizing coupling to bulk waves that could produce spurious signals. This solved the "false target" problem in AN/FPS-113 Radar for the ESD Combat Grande SPO. Spurious responses were reduced by 30 dB (factor of 1000) below the delay line previously used.

Knowledge from this work was transitioned to industry for large-scale deployment in SAW-based detector systems. A filter bank was developed by Watkins-Johnson under contract to the AFAL Electronic Warfare Division at Wright Patterson AFB, and was transitioned for use in B1-B and F-22 aircraft.

## References:

Dr. Paul Carr (AFRL/RHYA), private communication

A.J. Slobodnik, Jr., J. H. Silva, W. J. Kearns, and T. L. Szabo. "Lithium tantalate SAW substrate minimal diffraction cuts," IEEE Trans. Sonics and Ultrasonics 25 (1978) 92-97

### **3.9 First Rapid Thermal Processing of Semiconductor wafers, using Incandescent lamps (1982)**

#### IN-HOUSE RESEARCH ACHIEVEMENT

Annealing processes are widespread in electronic and optoelectronic device processing because of the need to restore crystal quality after damage caused by etching processes, ion implantation, etc., and also to redistribute ("drive") intentionally introduced electronic defects ("dopants"). Furnace annealing was nearly universal, but was often unsatisfactory: because of the thermal inertia of furnaces, atomic and defect diffusion could not be precisely tailored.

"Rapid Thermal Annealing" (RTA) methods were invented because of increasing needs to control diffusion better, enabling fabrication of abrupt p-n junctions and heterojunctions, activation of implanted impurities, etc.

AFRL/RYHC scientists and engineers therefore employed high-intensity incandescent lamps in their indium phosphide (InP) optoelectronic device processing to achieve improved thermal profiles with low thermal inertia. Still better results were achieved as the (opto)electronics industry moved to more intense light sources such as halogen lamps.

Source: Joseph Lorenzo (AFRL/RYHC), private communications

### **3.10 Phase-Only Optical Correlators for Image and Target Identification (1984-1993)**

#### IN-HOUSE RESEARCH ACHIEVEMENT

For decades, optical methods for pattern recognition have been the focus of intense research and applications. RYHC scientists made many internationally-celebrated contributions. They pioneered efficient all-optical processing methods relevant to the identification of images such as those of military targets, human faces, and fingerprints. Contributions by Dr. Joseph Horner and his RYHC collaborators spanned theory, experiment, and system demonstrations, especially in optical correlation (a specialized but powerful variation of the matched filter).

Dr. Horner and others demonstrated that most of the useful information in image correlation comes from the phase, not the amplitude, of the optical signals. Eliminating amplitude information actually improved optical filter performance. (Basically, this is because amplitude information records the low spatial frequencies, whereas phase records the higher spatial frequencies. This is analogous to using a high-pass filter in electronics or RF.) Phase-only filters (POFs) became a powerful optical processing tool.

In the course of this work Dr. Horner introduced a criterion for evaluating the light efficiency of optical correlators that stands alongside signal-to-noise ratio and peak correlation energy. It became universally known as the *Horner efficiency*.

Dr. Horner and his team then showed that binarizing the phase – i.e., making the signal phase either zero or 180 degrees – preserved most of the advantages of the POF, with little important degradation of key correlation properties. Most important, these binary phase-only filters (BPOFs) were well-suited to digital processing and for taking advantage of then-emerging spatial light modulator technologies. The power of BPOFs was a consequence of the fact that coherent optical processors could perform correlations in a fraction of a nanosecond, independent of the number of pixels in the image: they were massively parallel processors. Although this advantage was limited by practical shortcomings of SLMs, and was later eroded by advances in digital computer hardware, optical correlation methods have continued to be useful in digital as well as analog image processing.

RYHC transferred BPOF methods to Optikey, Inc., for facial recognition, and also created and patented fingerprint identification/matching methods. To demonstrate the BPOF's applicability to tracking and identifying military targets, RYH participated in DARPA/MTO's TOPS (Transition to Optical Processing Systems) Program. A prototype target ID and tracking system built by Martin Marietta was successfully field-tested during the early 1990's. The pattern recognition system performance for acquiring and identifying M60A2 tanks, arrayed among other vehicles, correctly identified tanks with 90% probability and with a 4% false identification rate. The system was flown in a helicopter; a video made during the TOPS test showed performance in real-time, including successful identification of tanks that were obscured 50% or more (the video was shown several times by Dr. Charles Woods of AFRL/Ryhc).

Dr. Joseph Horner was named a Fellow of the Optical Society of America, a Fellow of SPIE, and an AFRL Fellow. He received the Inventor of the Year Award from the Inventor's Association of New England, and an *Aviation Week & Space Technology* magazine Laureate Award.

#### References:

J.L. Horner, U.S. Patent 4,588,260 (1984) "Binary phase-only filter for use in an optical correlation system"

J.L. Horner & J. R. Leger, U.S. Patent 4,765,714 (1988), "Binary phase-only optical correlation system"

J.L. Horner & P.D. Gianino, "Phase-only matched filtering," *Appl. Optics* 23 (1984) 812.

D.L. Flannery & J.L. Horner, "Fourier Optical Signal Processors," Proc. IEEE 77 (1989) 1511.

B. Javidi, H. J. Caulfield, and J. L. Horner, "Image deconvolution by nonlinear signal processing," Appl. Optics 28 (1989) 3106.

Lasers & Optronics magazine, May 1989, p. 28

K. H. Fielding, J. L. Horner, and C. L. Makekau, "Optical fingerprint identification by binary joint transform correlation," Optical Engineering, 30 (1991) 1958

Scott. D. Lindell, "Summary of the transfer of optical processing to systems optical pattern recognition program," Proc. SPIE 2489 (1955) 20 doi.10.1117/12.212041

### **3.11 Digital Beamforming; Conformal Antennas (1985-2010)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

Digital beamforming (DBF) was created and developed to enable flexible, versatile control of antenna patterns for non-planar as well as planar arrays. In DBF, signals are digitized at the level of individual antenna array elements. Signals are then processed – assigning weights to the signals from individual elements or groups of elements -- in a digital processor to form the desired beam. Because the signals are digitized, they can be manipulated indefinitely without incurring further errors (which might not be the case for manipulating the real received signal power). Total information is preserved at the aperture level.

Under the leadership of Dr. Hans Steyskal, RYHA was an early and continuing leader in DBF, as well as an evangelizer for the technique. Because of hardware limitations, DBF originally was more practical in receive mode rather than in transmit mode. As electronic hardware improves, DBF on transmit will become increasingly practical and less expensive to implement; RYHA's contributions therefore will continue to exert pervasive long-term influences on antenna design and applications.

DBF applications include beam control for non-planar (including "conformal") antennas, ultra-low antenna sidelobes, antenna self-calibration, pattern correction to compensate for failure of array elements, creation of closely spaced multiple beams, and adaptive space-time processing. The *Aviation Week* reference below describes a conformal antenna built by Dr. Steyskal and collaborators in RYHA.

Also see the section, "Phased Array Error Correction (1993)," below.

Dr. Steyskal is a Fellow of the IEEE and an AFRL Fellow.

## References.

H. Steyskal, "Digital Beamforming Antennas -- An Introduction," Microwave Journal, Jan. 1987, p. 107ff;

H. Steyskal & J.F. Rose, "Digital Beamforming for Radar Systems," Microwave Journal, Jan. 1989, p. 121 ff.;

H. Steyskal, "Digital Beamforming at Rome Laboratory," Microwave Journal, Feb 1, 1996, pp. 100-126.

Aviation Week & Space Technology, April 15, 2002, p. 66 -- describes and has a photo of an RYHA conformal antenna that was empowered by digital beamforming.

R. L. Haupt, *Antenna Arrays. A Computational Approach*, J.W. Wiley (2010), pp. 455-456

## **3.12 Growth of space-qualified, fracture-resistant quartz crystals (1985)**

### IN-HOUSE RESEARCH ACHIEVEMENT with CONTRACTOR COLLABORATION

During the development of GPS satellite systems it was discovered that the resonant frequency of quartz used in GPS oscillators was altered by radiation damage from the space environment. This potentially fatal flaw was addressed and corrected by an RYHX in-house team led by Dr. Alton Armington, collaborating with Prof. J. J. Martin of the Oklahoma State University Physics Department.

In GPS satellites, atomic clocks provide the ultra-precise timing signal. However, the output of atomic clocks is not strong enough to power electronic circuitry. Therefore, the output of the atomic clock is used to "lock" a quartz oscillator, which in turn provides sufficient signal strength to drive the GPS circuitry.

Radiation in the GPS satellite environment produced defects in the quartz that shifted its oscillation frequency. This shift could unlock the quartz oscillator from the atomic clock frequency, disabling the GPS oscillator electronics. The RYHX team was asked to investigate the problem. Painstaking research they conducted in collaboration with Oklahoma State University (OSU), traced the radiation sensitivity to aluminum impurities in the quartz: upon irradiation, many of the impurities converted into an aluminum-hole defect. The RYH-OSU team effectively eliminated the defect center by growing quartz crystals that contained sharply reduced aluminum impurity concentrations.

Another problem the RYH-OSU team addressed was that quartz crystals were fragile because they contained high densities of dislocation defects. In the course of their research on quartz crystal growth, the RYHX researchers developed techniques that produced extremely low

dislocation density seeds for hydrothermal quartz growth. They ultimately reduced dislocation densities to as little as *one dislocation per square centimeter*! The unprecedented mechanical strength of this quartz made it suitable not only for GPS satellite launches, but also for fuzes in artillery shells (which undergo extreme acceleration when the shell is fired); therefore, it was transitioned to the Army.

The RYHX hydrothermal growth process was scaled up and transferred to Motorola; subsequently, the RYHX quartz team received an Award from the Federal Laboratory Consortium for Technology Transfer.

#### References:

This narrative draws from unpublished summaries and private communications by the late Dr. John J. Larkin

A.F. Armington and J. J. Larkin, J. Crystal Growth 71 (1985) 799

A. F. Armington, Progress in Crystal Growth and Characterization 21 (1990) 97

A. F. Armington and J. J. Larkin, "Quartz Growth on X-Seeds," U.S. Patent 4,576,808 (March 18, 1986)

### **3.13 Silicon Photonics and Optoelectronic Integrated Circuits (1986-2011)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

In terms of significant impacts over the long term, silicon photonics (a field that has now broadened into Group IV photonics) may rank among the most far-reaching technological contributions made by any Federal government laboratory.

In the 1980s and throughout most of the 1990s, silicon didn't get much respect among optoelectronics scientists and engineers -- a stark contrast with silicon's unquestioned importance in electronics technology. This lack of respect was due to the fact that silicon's conduction band minimum is not directly above its valence band maximum in energy band diagrams. This "indirect band gap" means that, in silicon, light emission and absorption processes are inefficient. "Silicon photonics (optoelectronics)" seemed to be an oxymoron.

Dr. Richard Soref of AFRL/RYHC and his collaborators changed that – dramatically. They fabricated practical optical waveguides in and on silicon wafers. Soon they moved on to invent more sophisticated optoelectronic components, like current-injection optical modulators,

switches, and signal splitters. Several of these device concepts formed the basis for later silicon-based optoelectronic devices (see, e.g., the *Physics Today* article listed below).

A few years later, Dr. Soref articulated a vision of optoelectronic “superchips,” an optical analog to high density electronic integrated circuits on silicon (see Dr. Soref’s Proc. IEEE article, listed below) and became one of its most prominent avatars. Silicon-based optoelectronics (as it was known, then) began to attract more and more outstanding researchers, and expanded its repertoire to include alloys with the Group IV semiconductors germanium (Ge), tin (Sn), tri-element alloys of Si, Ge, and Sn, and a host of novel structures such as quantum wells. Dr. Soref in 2004 founded the IEEE LEOS (now IEEE Photonics Society) International Conferences on Group IV Photonics, which have continued and gained prominence.

Intel Corporation, IBM, and other mainline electronic integrated circuit manufacturers now conduct serious Group IV photonics R&D efforts to (among other things) to replace on-chip and inter-chip copper wiring with optical signal transmission (see article, “The Silicon Solution,” listed below). Seeking to leverage the enormous silicon manufacturing infrastructure and its low-cost production techniques, a Group IV optics integrated circuit research foundry (supported by the AF Office of Scientific Research) was recently established at the University of Delaware.

#### References:

R. A. Soref and J. P. Lorenzo, “All-silicon active and passive guided-wave components for  $\lambda = 1.3$  and  $1.6 \mu\text{m}$ ,” IEEE J. Quantum Electronics QE-22 (June 1986) 873-879. [First research paper in the field]

R. A. Soref and B. R. Bennett, “Kramers–Kronig analysis of E–O switching in silicon,” Proc. SPIE Integr. Opt. Circuit Eng., 704 (1986) 32–37.

R. A. Soref and B. R. Bennett, “Electrooptical effects in silicon,” IEEE J. Quantum Electronics QE-23 (January 1987) 123-129

R. A. Soref, “Silicon-Based Optoelectronics,” Proc. IEEE 81 (Dec 1993) 1687-1706

“New Silicon-Based Device Modulates Light at 1 GHz,” *Physics Today*, April 2004, p. 24

For glimpses of how important silicon photonics is becoming, see:

G. T. Reed, “The Optical Age of Silicon,” *Nature* 427 (12 Feb 2004) 595;

M. Paniccia and S. Koehl, “The Silicon Solution,” *IEEE Spectrum*, Oct 2005, pp. 38-43.

C. Gunn, “Silicon Photonics Poised to Invade Local Area Networks,” *Photonics Spectra*, March 2006, pp. 62-67;

L. Wood, "Shining a light on the chip-interconnect bottleneck," Computerworld, Feb 9, 2011

### **3.14 Histogram Projection Algorithm (1988)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

The histogram projection algorithm, created by Drs. Jerry Silverman and Jonathan Mooney of RYHI, originally provided real-time, fully automatic contrast conversion from 14-bit IR data (recorded by PtSi cameras) to the 8-bit cockpit displays of its time. Afterward, this image processing method became widely employed by the Air Force, DoD, and industry. Since it is broadly applicable, the algorithm has been used for IR cameras utilizing detector arrays other than PtSi.

More specifically: Problems of extreme signal dynamic range and dominant background noise in staring IR thermal imagery, addressed in RYHI's PtSi-camera program, follow from photon-dynamics thermal infrared signal and backgrounds. Therefore, the Silverman-Mooney algorithm is generally applicable.

#### References:

J. Silverman and J. M. Mooney, "Processing for IR images from PtSi Schottky barrier detector arrays" Proc. SPIE, Vol. 974, Applications of Digital Image Processing XI, pp. 300-309, 1988.

J. Silverman, J. M. Mooney, and V. E. Vickers, "Display of wide dynamic range infrared images from PtSi Schottky barrier cameras," Optical Engineering 29 (1990) 97-104

J. Silverman and V. E. Vickers, "Display and enhancement of infrared images," Chapt. 15 of *Electro-Optical Displays*, M. A. Karim, editor, Marcel Dekker, New York, 1992

### **3.15 Intrusion-Detecting Optical Communications System (IDOCS) (1984-1988)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

IDOCS was the first nonencrypted data link to be certified as secure by the National Security Agency (June 1988). It was first deployed at HQ, Alaskan Air Command, Elmendorf AFB (December 1988).

The basis of IDOCS was dual-channel transmission on step-index optical fiber, which was readily available at the time. Low-order fiber modes were used to transmit sensitive data, whereas high-order modes were used to send a monitor signal. The receiver sensed the balance between the low-mode and high-mode signals, and would shut down the system and generate an alarm if the balance were to be disrupted, e.g., by someone attempting to “tap” the link.

#### References:

Lasers & Optronics magazine, May 1989, pp. 26-28

Contemporaneous RYHC briefing chart (unpublished)

### **3.16 Platinum Silicide Infrared Focal Plane Array (IRFPA) Cameras (1990-1996)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

The creation, technology transfers, and technology transitions of PtSi IRFPA cameras were the culmination of a constellation of major RYHI advances in infrared and focal plane array (FPA) technologies. (For background on FPAs and PtSi device technology, see the section, above: “Staring Infrared (IR) Focal Plane Array (FPA) Technology (1975+).”)

A comparatively early PtSi camera (a “pushbroom” camera), employed on a U-2 during the Gulf War (Operation Desert Storm) “mapped” Iraqi mine fields and associated battlefield obstacles (an image was published in *Aviation Week & Space Technology* magazine, August 19, 1991). It was also used to discover mass grave sites during the Balkans campaign of the late 1990s, a key factor in proving that war crimes had been committed.

More advanced PtSi cameras, having staring focal plane arrays, were installed on the entire B-52 fleet (approx. 1995), following an Advanced Technology Transition Demonstration, and on Predator UAVs. B-52 prototype cameras were built in-house by an AFRL/RYHI team led by Dr. William Ewing. The final prototype was test-flown on B-52s in the technology transition managed by a team led by John O’Brien at the Warner Robins AFB Air Logistics Center.

The PtSi history has often been cited as an example of how patient support of basic research can result in important military products and capabilities. This version of the story is woefully incomplete. While it is true that approximately 25 years elapsed between RYHI’s first AFOSR-supported basic research studies and the transition of PtSi cameras to the B-52 fleet, many other important, but not as well-known, technology transfers and transitions occurred during the intervening years. In many ways, RYHI’s PtSi research revolutionized the science and technology of infrared imaging. Aside from the U-2 PtSi camera and the Histogram Projection Algorithm (see above), five collateral scientific and technical advances deserve mention:

- Method for cleaning oxide from the surface of a silicon wafer (devised by Dr. Andrew Yang) that left a protected oxide-free silicon surface. The protective layer was removed by vacuum processing, followed by platinum evaporation to create the Schottky diode. This process was treated as an RYHI trade secret but shared, in confidence, with domestic firms that intended to develop PtSi imagers [see “Staring Infrared (IR) Focal Plane Array (FPA) Technology (1975+),” above)]. Several years later it was “rediscovered” and given its common name by a major electronics firm.
- Advances in understanding low-frequency noise (“1/f noise”) in imaging systems. RYHI’s PtSi cameras exhibited negligible 1/f noise.
- Understanding of “pattern noise” caused by fluctuations in pixel-to-pixel properties.
- Blackbody source for precise FPA calibration.
- Demonstrations, based on field testing, that in many relevant situations, mid-wave infrared (MWIR) imaging is superior to long-wave infrared (LWIR) imaging. Under humid conditions (this includes conditions above large bodies of water) and under many foggy conditions, MWIR imaging decisively outperforms LWIR imaging because water vapor attenuates LWIR atmospheric transmission; this insight had not been anticipated by the IR technical community at large. As a result of RYHI research and field tests, MWIR imagers have become a staple of military hardware. In that sense, RYHI “gave” the mid-IR band to DoD and the Air Force.

In recognition of RYHI-driven advances in IR technologies, the PtSi team won the DoD MSS Sir William Herschel Award, the DoD MSS Henry Levinston Award, and an *Aviation Week & Space Technology* magazine Laurels Award. The team’s leader, Dr. Freeman Shepherd, was elected to the National Academy of Engineering, and he won the 1988 Air Force Harold Brown Award (highest Air Force R&D award); he is a Fellow of the IEEE, a Fellow of the SPIE, and an AFRL Fellow.

#### References:

S. A. Roosild, F. D. Shepherd, Jr., A. C. Yang, and W. Shedd, U.S. Patent 3,902,066 (Aug 26, 1975), “Schottky Barrier Infrared Detector Arrays With Charge Coupled Device Readout”

J. Silverman, J. M. Mooney, and F. D. Shepherd, “Infrared Video Cameras,” *Scientific American* 266 (Mar 1992) 78

F. D. Shepherd, “Infrared Internal Emission Detectors,” *Proc. SPIE* 1735 (1992) 250

J. M. Mooney, “Excess Low-Frequency Noise in PtSi on p-Type Si Schottky Diodes,” *IEEE Transactions on Electron Devices* 38 (Jan 1991) 160

F. D. Shepherd, J. O’Brien, W. S. Ewing, R. W. Taylor and S. DiSalvo, “B52 IR Camera Advanced Technology Transition Demonstration (ATTD)”, IRIA-IRIS Report, No. 213400-131-X(1), 1992 Meeting of the IRIS Specialty Group on Passive Sensors, Ed. M. Cantella, Vol. 1 pp. 333-345, 1992.

B. A. Smith, "U-2/TR-1s Provide Critical Data to Theater Commanders," *Aviation Week & Space Technology*, August 19, 1991, p. 60.

### **3.17 Microwave Laser Module (1991)**

#### **IN-HOUSE AND CONTRACT RESEARCH ACHIEVEMENT**

This device was a directly modulated 20 GHz bandwidth microwave laser transmitter developed by Lasertron, Inc. under an SBIR contract managed by Mr. Charles Tsacoyeanes (AFRL/RYHC). It emitted 1.3 micrometer wavelength laser radiation to transmit microwave signals reliably over single-mode optical fiber. The transmitter was used in many military and commercial applications, and won a 1991 *R&D 100 Award* (Lasertron and USAF Rome Laboratory, parent organization for RYH, were both cited). For more than 5 years it was the highest bandwidth transmitter available commercially.

In addition to the technology transfer of the Microwave Laser Module itself, the diamond heat-sink mount technology created by Lasertron and Mr. Tsacoyeanes in this program was spun off into commercial components.

#### References:

Research & Development Magazine, October 1991, p.59.

<http://www.rdmag.com/RD100SearchResults.aspx?&intYear=1991&Type=Y>

### **3.18 "Showerhead" MOCVD Thin Film Semiconductor Deposition Technology (1991)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

The close-spaced ("showerhead") metal-organic chemical vapor deposition (MOCVD) reactor was invented by Drs. David Weyburne and Brian Ahern (RYHX) to create more uniform, better-controlled III-V semiconductor thin films and multilayer structures for improved RF and optoelectronic/photonic device structures. The showerhead reactor was a significant departure from conventional MOCVD reactors, which inject gaseous reactants 10-15 cm from the heated semiconductor substrate (the large spacing was needed to insure that reactants break down on the surface of the substrate rather than in the injector).

In the showerhead (originally dubbed the ACE, or Actively Cooled Effuser), MOCVD reactant gases come through holes or slots in a flat perforated plate that resembles a flat showerhead.

Water-cooling the injector makes it possible to reduce the injector-substrate spacing to as little as 1 cm without semiconductor materials solidifying on the injector itself. Nearly laminar flow of reactant gases can be achieved, resulting in thin film layers that had unprecedented flatness, and in semiconductor alloy film compositions of unsurpassed homogeneity. Moreover, the showerhead more efficiently uses expensive chemical reactants: in GaAs deposition, for example, up to 25% of Ga from trimethylgallium was deposited on the substrate, compared to approximately 5% in a conventional MOCVD reactor configuration).

Showerhead technology was transferred to Spire Corp via a Phase II SBIR contract (1993). For a few years thereafter, Spire marketed showerhead products it had developed. Showerhead injectors were subsequently produced and marketed by Thomas Swan, Inc. (a unit of Aixtron), a major manufacturer of MOCVD equipment. It was also adopted by other manufacturers, and became a gold standard for MOCVD deposition of nitride semiconductors used for high-power RF electronics, ultraviolet/violet/blue LEDs & lasers, and white-light LEDs.

Showerhead technology produces outstanding layer structures for RF and optoelectronic devices; it is widely employed for depositing wide-bandgap nitride semiconductors for LED lighting devices and high power RF transmitter amplifiers.

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D. W. Weyburne and B. S. Ahern, "Design and operating considerations for a water-cooled close-spaced reactant injector in a production scale MOCVD reactor," Journal of Crystal Growth 170 (1997) 77

### 3.19 Advances in Indium Phosphide (InP) Science and Technologies (1992-2003)

#### IN-HOUSE RESEARCH ACHIEVEMENT

Over approximately an entire decade, research conducted by RYHX S&Es and their collaborators, led by Dr. David Bliss, made groundbreaking contributions to indium phosphide (InP) science and technology. They enlarged fundamental understanding of InP semiconductor properties, bulk crystal growth methods, and wafer technology. These advances resulted in major technology transfers that helped to accelerate military and industrial applications of InP. InP and its alloys have been prized for device applications in high-speed RF and digital devices, high-speed near-infrared detectors and lasers/detectors for telecom and “eye-safe” systems.

RYHX’s magnetic field liquid encapsulated Czochralski (MLEC) and Kyropoulos (MLEK) bulk crystal growth methods showed the InP community how to minimize destructive crystallographic twin defects in <100>-oriented InP (the wafer orientation required for modern electronic/optoelectronic devices and circuits) bulk crystals, making it possible to increase wafer yield significantly. The same techniques reduced the concentration of dislocation defects and markedly increased crystal uniformity. The techniques also permitted the RYH team to grow 3 inch diameter high quality InP single crystals repeatably when the state of the art was 2 inches, as well as the first 4-inch-diameter crystals. Employing an AFRL/RYS-sponsored Dual Use S&T contract with Tyco Electronics, they transferred 4 inch diameter growth technology to industry.

RYHX scientists analyzed and improved phosphorus injection synthesis -- injection of phosphorus into molten indium to form InP. Industry had employed phosphorus injection to synthesize polycrystalline InP “charges.” In standard practice, a “charge” was synthesized, cleaned, placed in a crystal growth furnace, and pulled into a single crystal. The process typically consumed approximately 4 days from synthesis through crystal growth. Dr. Bliss and his team devised a process in which injection synthesis was conducted *within the crystal growth apparatus*, so that immediately after synthesis, single crystal ingots were grown – all within a single day.

In collaborations with scientists at Lawrence Berkeley National Laboratory, hydrogen impurities were shown to increase the free electron concentration of nominally undoped InP, solving the long-standing conundrum of “excess donors.” Elimination of these “excess donors” (hydrogen-related defects) by wafer annealing, together with use of the RYHX phosphorus injection methods, made it possible to reduce the amount of iron that must be intentionally dissolved into (“doped into”) InP to fabricate ultra-high-resistivity (“semi-insulating”) wafers for high-speed, high-power microwave and photorefractive applications. Also, in the course of this work, RYHX and collaborators advanced the fundamental understanding of how electron carrier concentrations in InP are affected by the ratio of Fe(2+) and Fe(3+) impurity centers.

These experimental successes led to pioneering collaborations with researchers in crystal growth modeling and simulation, highlighted by an AFOSR-sponsored MURI (Multidisciplinary University Research Initiative) in which, for the first time ever, theoretical simulation techniques and codes were refined by feedback from actual crystal growth experiments. The theoreticians sought not only to predict the characteristics of crystals grown by RYH, but also – in a departure designed to improve the robustness of their models and codes – the temperature profiles and other characteristics of the RYH crystal growth system (which were measured by the RYH researchers). The success of this collaboration prompted AFOSR to sponsor an STTR contract to implement the RYH-MURI crystal growth technology. GT Equipment Technology (Nashua, NH), the STTR contractor, then marketed their next-generation system for growth of advanced semiconductor crystals.

Dr. David Bliss was a President of the American Association for Crystal Growth.

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D. F. Bliss, R. M. Hilton, J. A. Adamski (Parke Mathematical Lab), W. M. Higgins (Parke Mathematical Lab), and V. Prasad (SUNY-Stony Brook University) "Phosphorus-Rich InP Grown by a One Step 'In Situ' MLEK Crystal Growth Process," *Proceedings of the Fifth International Conference on Indium Phosphide and Related Materials*, April 1993.

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M. Prairie (AFOSR), "Ground-, Space-Based Systems Will Exchange More Information Faster," AFOSR Research Highlights, Jan-Feb 1998

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### **3.20 Phased Array Error Correction (1993+)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

In addition to providing electronic (rather than mechanical) scanning, phased array antennas have made possible a degree of antenna sidelobe control never possible with reflector or lens scanning systems. However, in order to minimize sidelobes, there is a need for accurate control of phasing devices and for failures to be detected and compensated. AFRL/Ryha became a leader in this technology through its in-house research, complemented by contractual efforts.

#### References:

R.J. Mailloux, "Phased Array Error Correction Scheme," *Electronics Letters*, Vol.29, No.7, 1 Apr. 1993, pp. 573-574

T.H. O'Donnell, H.L. Southall, R.J. Mailloux, "Source Synthesis for Training Array Neural Networks," *Electronics Letters*, 16 Feb 1995, Vol. 31, No. 4, pp. 298-299

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R.J. Mailloux, "Operating modes and dynamic range of active space fed arrays with digital beamforming," *IEEE Trans. Antennas & Propagation*, AP-54, No.11, Nov.2006

### **3.21 Optoelectronic Devices from Wafer Fusion Technology (1995)**

CONTRACTOR RESEARCH ACHIEVEMENT (Prof. John Bowers group -- University of California at Santa Barbara); Program Manager was Charles W. Tsacoyeanes, AFRL/RyHC

Wafer Fusion is a fabrication technique that enables joining of dissimilar semiconductor substrates (wafers), so devices can exploit the desirable properties of each material. The wafer bonding process consists of placing the two in close contact, annealing them at elevated temperatures (400-1200 degrees centigrade), and at the same time applying uniaxial pressure to the wafers.

The technique was originally developed with RyHC support at MIT Lincoln Laboratory in 1990. It was further developed at UCSB, resulting in several optoelectronic devices, and subsequently transitioned to industry. Devices developed using wafer fusion include: light emitting diodes (LEDs), vertical cavity surface emitting lasers (VCSELs), microstrip lasers, resonant cavity photodetectors, and avalanche photodiodes (APDs).

At UCSB, LEDs were typically fabricated by growing an AlGaInP alloy that was lattice-matched to its GaAs substrate. Because the LED's external quantum efficiency was limited by optical absorption in the GaAs substrate, UCSB selectively removed the GaAs, using chemical etching, and wafer-bonded it to a transparent GaP substrate. The quantum efficiency doubled.

The wafer fusion technology was transitioned to Hewlett Packard (HP) and used to develop the world's brightest LED material, using TS (Transparent-Substrate) AlInGaP technology. This device had the highest luminous and external efficiency of any LED technology. The external efficiency exceeded all LED technologies by a factor of more than 2 in the green to red spectral regime. Beginning in 1995, HP used this technology in their high-volume production of visible LEDs.

#### References:

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### **3.22 First room-temperature InP-based 1.55 micron wavelength CW Vertical Cavity Surface-Emitting Laser (VCSEL) (1995)**

CONTRACTOR RESEARCH ACHIEVEMENT -- U. California at Santa Barbara (Prof. John Bowers' group); Program Manager was Charles W. Tsacoyeanes, AFRL/RyHC

World record performance was obtained from a long wavelength vertical cavity surface emitting laser (VCSEL). Room temperature continuous wave (CW) operation was demonstrated for the first time. This performance was obtained from a new structure, which lased at a wavelength of 1.55 micrometers – the fiber-optic telecom standard, and a wavelength that also is eye-safe. Compared to edge-emitting, cleaved devices, laser transmitters using VCSELs provided higher data rates with much lower bias currents, higher wall-plug efficiency, single longitudinal mode without a grating, a narrow circular beam, and smaller beam divergence. Optics requirements were therefore simpler for VCSELs than for edge-emitting lasers. Other advantages included low threshold current, high modulation speed, ability to fabricate high density two-dimensional arrays, wafer level testing, no mirror cleaving, and less temperature dependence.

The new VCSEL structure was fabricated by using wafer fusion to join GaAs-based mirrors with the InP-based active region. This novel structure contained an active region with seven compressively strained InGaAsP quantum wells with strain compensating barriers, a top p-doped AlGaAs/GaAs quarter-wave mirror stack, and a bottom n-doped AlAs/GaAs quarter-wave mirror stack. Further improvement in performance was obtained by using an AlAs oxide aperture, resulting in a record low threshold current of 0.8 ma.

#### References:

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K. W. Carey, L. Yang, J. E. Bowers, D. I. Babic, J. J. Dudley, U. S. Patent 6,277,696 (21 Aug 2001), "Surface Emitting Laser Using Two Wafer Bonded Mirrors"

### **3.23 Recapturing Leadership in Gallium Arsenide (GaAs) Wafer Technologies for the US (1996)**

#### **CONTRACTOR R&D ACHIEVEMENT (US GaAs manufacturers)**

To help U.S. GaAs wafer producers cope with the onslaught of ruinous foreign competition, a Title III (Defense Production Act) Program was instituted by the AFRL Materials Directorate (Ms. Laura Rea) and the AFRL Title III Program Office (Mr. John Blevins). RYH (Drs. David Bliss and David Weyburne) contributed Subject Matter technical expertise on crystal growth and processing of wafers from the bulk crystal ingots.

Before this program, US vendors were marginally competitive compared to foreign GaAs manufacturers. This was of enormous concern because high power RF semiconductor devices and circuits were increasingly the province of GaAs and because many military and civilian optoelectronic devices were based on GaAs.

During the Title III program, domestic GaAs wafer quality was significantly improved, and wafer diameters were upgraded from 4 to 6 inches (an enabler for lowering costs because more devices could be fabricated on each wafer). This enabled US industry to meet and even exceed the quality of wafers supplied by foreign competitors. Whereas foreign GaAs manufacturers held a 75 percent market share before the Title III program, by 2000 the Title III contractors accounted for 65 percent of GaAs wafer sales worldwide.

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Ronald M. Sega, testimony before U.S. Senate Committee on Banking, Housing, and Urban Affairs, June 5, 2003. [http://banking.senate.gov/03\\_06hr/060503/sega.pdf](http://banking.senate.gov/03_06hr/060503/sega.pdf)

### **3.24 Antennas designed using genetic algorithms (GA) and related evolutionary algorithms (1998+)**

#### IN-HOUSE RESEARCH ACHIEVEMENT

Genetic and other evolutionary algorithms are powerful optimization methods for finding improved designs. When applied to wire antennas by Dr. Edward Altshuler and collaborators from RYHA and elsewhere, they led to antenna configurations that were not intuitively obvious (except, sometimes, in hindsight).

An early practical RYHA application of GA to antennas was to improve the AF Weather Agency’s DISS (Digital Ionospheric Sounding System) antenna. The GA optimization yielded a low-cost modification to the existing DISS system that filled holes in antenna coverage and increased the system gain. The GA approach was also transitioned to the National Reconnaissance Office (NRO) to design two antennas to sense electromagnetic fields near an NRO satellite prior to launch, to verify that satellite electronics would not be damaged by a strong electromagnetic pulse. GA was also used to design an antenna for NASA’s Space Technology 5 (STS5) spacecraft – part of NASA’s New Millennium Program missions that launches multiple miniature spacecraft to test innovative concepts and technologies in harsh space environments.

The reference by Santarelli *et al.* reviews RYH’s work on genetic algorithms up to 2006.

For his contributions to antenna theory, Dr. Altshuler received the IEEE Harry Diamond Award; he is a Fellow of the IEEE and an AFRL Fellow.

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Edward E. Altshuler and Derek S. Linden, U.S. Patent 5,719,794 (Feb 17, 1998), "Process for the design of antennas using genetic algorithms" [First use of genetic algorithm to design an antenna]

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### **3.25 High-Gain, High-Speed, Near-Infrared Avalanche Photodiode (1998)**

CONTRACT RESEARCH ACHIEVEMENT – Prof. John Bowers group --University of California, Santa Barbara; Program Mgr, Charles W. Tsacoyeanes, AFRL/RyHC

The avalanche photodiode (APD) is an optical semiconductor detector that can amplify the detected signal (a semiconductor analog to the photomultiplier tube). World record performance was obtained from a new high performance near-infrared (1.0 to 1.6 micrometer wavelength) APD, created at the University of California, Santa Barbara. This device had substantially higher sensitivity, higher speed, lower noise, and higher temperature and voltage stability than any previous APDs in that wavelength range.

The structure of this APD was noteworthy for the innovative way in which wafer bonding/fusion methods were employed. Conventional near-infrared InGaAs/InP APDs are limited in performance by a small electron/hole ionization coefficient ratio, which results in low gain-bandwidth-product and high excess noise. On the other hand, silicon is an ideal material for APDs because its very high ionization coefficient ratio results in a high gain-bandwidth-product and very low excess noise. However, silicon unfortunately has a very low absorption coefficient at the fiber-optic and free-space optical communications wavelengths of 1.3 micrometers and 1.5 micrometers. UCSB overcame these respective drawbacks by wafer-bonding InGaAs to silicon. The UCSB InGaAs/Si APD structure separated absorption in the InGaAs region from carrier multiplication in the silicon (separate amplification and multiplication, or SAM structure). The result was much higher sensitivity, higher gain-bandwidth-product, lower noise, and higher temperature and voltage stability than any previous near-infrared photodetector.

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### **3.26 High-speed, Wide-bandwidth Near-infrared Photodetector (1999)**

CONTRACT RESEARCH ACHIEVEMENT, by Picometrix, Inc.; Program Mgr, Charles W. Tsacoyeanes, AFRL/RYHC

A high-speed, wide spectral width (900 – 1600 nanometers) photodetector created by Picometrix (Ann Arbor, MI), achieved world record performance. This device had substantially higher speed, higher sensitivity, lower noise, and lower leakage current than any other near-infrared photodetector. The device was an InGaAs PIN mesa-structured photodiode that was flip-chip bonded onto a standard 50 ohm launcher substrate and installed into a microwave module. Frequency response measurements showed a voltage bandwidth (-6 dB) of greater than 65 GHz (actually, the response was faster than could be measured using commercial diagnostics).

The R&D in this program resulted in several photoreceivers which remained commercially available more than ten years later.

Military applications included free-space and fiber-optic communications and antenna remoting. In addition, there is a large commercial telecommunications market for this device because high speed will enable faster data transmission over longer distances.

#### Reference:

J. A. Valdmanis and J. V. Rudd, "High-Speed Optical Signals Demand Quick Response," Laser Focus World, March 1995.

### **3.27 Bistatic Radar Cross Section (RCS) from Transformed Near-Field Measurements (2000+)**

#### IN-HOUSE RESEARCH ACHIEVEMENT

Theoretical and experimental methods and technology to determine a target's bistatic radar cross section (RCS) using near-field scattering measurements were created within the Electromagnetic Scattering Branch (RYHE), advancing the state of bistatic measurement techniques.

Improvements included reducing the test range physical space requirement, expanding the spatial data collection capability, and reducing measurement times, all of which contribute significantly to cost savings and effectiveness of the target characterization mission.

Conventional radar system designs have the transmitter and receiver sub-systems co-located. This configuration is termed *monostatic*. Here, the signal echoed from a target back to the radar, called the backscattered signal, is detected and processed. However, a target typically scatters energy in many other directions in addition to backscatter, and this more general phenomenon is termed *bistatic scattering*. Operationally, bistatic radar differs from monostatic by using a receiver that is not co-located with the transmitter to detect and measure the bistatic scattered signal. A defining parameter in this scenario is the bistatic angle  $\beta$ , which is the included angle of the transmitter-to-target and target-to-receiver paths. Backscatter is the case where  $\beta = 0$ . The target's RCS, a measure of the relative strength of the signal scattered toward the receiver, is a function of target orientation with respect to the platforms and the bistatic angle, as well as the frequency and polarization of the radar beam.

Typically, measuring the monostatic RCS of a full-size target requires 1) extensive real estate for the necessary separation between the measurement system and target, or 2) a sizeable indoor anechoic chamber with a compact range reflector to form a planar incident wave. Measurement of bistatic RCS also involves the use of either of these options, but with additional space requirements to accommodate receiver positions for all the desired bistatic measurement geometries. Also, far-field or compact range-based techniques only allow measurements in a single elevation plane, with limited target reorientation (and the associated positioning challenges) allowing some degree of "non-waterline" data collection. Such far-field measurements have been undertaken on large outdoor ranges, but they are subject to lengthy set-up times and inherent challenges of weather and of ensuring security.

The new methods developed in RYHE use a single near-field microwave probe that rapidly scans an imaginary cylindrical surface around the target under test; the compact range provides the incident plane wave. Sampling the scattered field in this manner produces a range of bistatic measurements in a single scan. Mathematical transformation of the near-field data to the far field provides bistatic RCS values over the large range of azimuth and elevation scattering angles sought. An IEEE reviewer called the development of these mathematical transformations and verifications a "... substantial improvements in the theory of near-field measurements."

As a means of validating the approach, canonical bodies, such as spheres and cylinders, were measured; the results compared extremely well with the theoretically known signatures. To validate results of scale model target measurements where the RCS could not be theoretically computed, a second compact range reflector was mounted on a wheeled frame to serve as a bistatic far-field receiver. Further improvements, such as the use of field probe array and pulse waveform techniques to substantially reduce measurement times, were being explored until the closure of the Hanscom Research Site, due to BRAC, during the summer of 2011.

#### References:

T.B. Hansen, R.A. Marr, U.H.W. Lammers, T.J. Tanigawa, R.V. McGahan, "Bistatic RCS Calculations From Cylindrical Near-Field Measurements -- Part I: Theory," IEEE Transactions on Antennas and Propagation, AP-54, (Dec 2006), 3846-3856

R.A. Marr, U.H.W. Lammers, T.B. Hansen, T.J. Tanigawa and R.V. McGahan, "Bistatic RCS Calculations From Cylindrical Near-Field Measurements -- Part II: Experiments," IEEE Transactions on Antennas and Propagation, AP-54, (Dec 2006), 3857-3864

### **3.28 First slowing, stopping, and restarting of a light beam in a solid material (2001)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

Following the pioneering work at Harvard, in which a team led by Professor Lene Hau slowed, stopped, and re-started a light beam in a specially prepared cold gas, Dr. Philip Hemmer (AFRL/RYHC) led a team that performed the same feat in a solid. Dr. Hemmer's team (researchers from RYHC and MIT) used a crystal of yttrium silicate that contained a small concentration of praseodymium (Pr) impurities. A laser pulse illuminated the solid, and a second beam coupled the pulse to localized electron energy levels of the Pr. Because the laser pulse proceeds through the crystal by a process of absorption followed by re-emission followed by absorption, etc., this specially prepared coupling slows down the pulse by transferring its energy to the impurity energy levels.

When the coupling (illumination by the second beam) was strong enough, propagation of the light pulse could be stopped entirely. Then, by appropriately changing the intensity of the coupling beam, the Pr impurities were induced to re-emit photons and "re-start" the light pulse.

Such use of light to control light propagation has applications in variable optical delays for signal processing and data buffering, for optical shift register devices, and for information storage for quantum computing.

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A.V. Turukhin et al., "Observation of Ultraslow and Stored Light Pulses in a Solid" Phys. Rev. Lett. 88 (2001) 023602

### **3.29 Incremental Length Diffraction Coefficients for 3-Dimensional Bodies (2001)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

This theoretical technique was devised by Dr. Robert Shore and Dr. Arthur Yaghjian (RYHE) to calculate the way that radar waves actually scatter off bodies such as aircraft. Ordinary ray-tracing predicts that the aircraft casts a shadow. However, because of diffraction effects and surface waves excited on the skin of the aircraft, some of the radio-frequency electromagnetic illumination can be detected on the “back side” of the aircraft (where the radar transmitter is “in front”). Bistatic radar can detect such backside scattering. The bistatic radar cross section (RCS) is of great military (as well as scientific) interest.

A more sophisticated and widely used theory known as the “Physical Optics” (PO) method treats electrical currents induced by an incoming wave at a point on the surface of a conducting scattering object as though they are currents induced on an infinite plane tangent to the surface at that point. This approximation is excellent for those points where the nearby surface looks locally much like a plane, but the approximation breaks down for points that are near edges, cracks, or shadow boundaries of the surface. The non-PO currents, also called “non-uniform currents”, can significantly affect the bistatic RCS, and so it is important to be able to capture this effect in bistatic RCS calculations.

The non-uniform currents are in general very complicated and very difficult to calculate. However, Drs. Shore and Yaghjian noticed that, for certain canonical objects such as the conducting half-plane, wedge, slit, strip, and circular cylinder, the fields produced by these non-uniform currents can be calculated, and expressed as an integral of the fields produced by incremental lengths of these canonical scatterers. These incremental fields produce what are known as Incremental Length Diffraction Coefficients (ILDCs). Given an actual scattering object with edges, cracks, surface discontinuities, shadow boundaries, etc., the method of ILDCs works by approximating the surface at these points by incremental pieces of the canonical scatters so that the effect of the portions of the surface that cannot be well approximated by the PO approximation can be well approximated by integrating the appropriate ILDCs along the edges, cracks, shadow boundaries. The method of ILDCs depends on the availability of having ILDCs for canonical scatterers.

The major achievement of Drs. Shore and Yaghjian was to develop a cook-book method for obtaining ILDCs of canonical scatterers given the far field due to the non-uniform currents on these canonical scatterers. Previously a laborious integration of the non-uniform currents was required to obtain ILDCs, and very few had been found. The Shore-Yaghjian method revolutionized this. Indeed, one reviewer of the Shore-Yaghjian manuscript on ILDCs, when they submitted it for publication, said that their method was “like the wave of a magic wand.” Their article won the 2002 S.A. Schelkunoff Prize for best paper of 2001 published in the IEEE Transactions on Antennas and Propagation.

The Air Force adopted the elegant, efficient Shore-Yaghjian theory in its widely-used XPATCH RCS computational code.

Drs. Shore and Yaghjian are Fellows of the IEEE.

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R. A. Shore and A. D. Yaghjian, "Shadow Boundary Incremental Length Diffraction Coefficients Applied to Scattering from 3-D Bodies," IEEE Transactions on Antennas and Propagation, AP-49 (Feb 2001) 200-210.

R. A. Shore and A. D. Yaghjian, "Incremental Diffraction Coefficients for Plane Conformal Strips with Application to Bistatic Scattering from the Disk, Jour. Electromagnetic Waves and Applications 6 (1992) 359-396.

<http://www.afrl.hpc.mil/software/info/xpatch/>

### **3.30 Dynamic Logic (a.k.a. Neural Modeling Fields Theory) (2001+)**

#### IN-HOUSE RESEARCH ACHIEVEMENT

Dynamic Logic (DL) is a versatile, efficient cognitive algorithmic framework that combines ideas from neural networks, fuzzy logic, and model-based recognition. During a DL computation, fuzzy and uncertain models are initially associated with structures in the input signals (e.g., straight lines for Ground Moving Target Indicator – GMTI – tracks). During successive iterations these and fuzzy models become more definite and crisp. The type, shape, and number, of models are selected so that the internal representation within the system is similar to input signals. The DL method is efficient, avoiding issues of computational complexity that plague template-matching target identification methods.

DL has been successfully applied to finding multiple targets in radar GMTI data, synthetic aperture radar (SAR) data for slow-moving targets, and other tracking problems. It is being applied to fusion of information and language (e.g., data and voice signals). Dr. Leonid Perlovsky, inventor of Dynamic Logic, has received the Neural Network Society Gabor Prize and the Air Force McLucas [basic research] Award.

#### References:

L. I. Perlovsky, *Neural Networks and Intellect: using model based concepts*. New York: Oxford University Press (2001)

Christopher W. Mutz, Leonid I. Perlovsky; and Robert J. Linnehan, U.S. Patent 6,911,933 (June 28, 2005), "Dynamic logic algorithm used for detecting slow-moving or concealed targets in synthetic aperture radar (SAR) images"

L. I. Perlovsky, "Cognitive High Level Information Fusion," Information Sciences 177 (15 May 2007) 2009-2118

L. I. Perlovsky and R.W. Deming, "Neural Networks for Improved Tracking," IEEE Trans. Neural Networks, 18 (2007) 1854

L. Perlovsky, "Language and Cognition," Neural Networks 22 (2009) 247-257

L. I. Perlovsky, R. W. Deming, and R. Ilin, (2011). *Emotional Cognitive Neural Algorithms with Engineering Applications. Dynamic Logic: from vague to crisp*. Springer, Heidelberg, Germany

### **3.31 Reliable determination of Energy Bandgap of Aluminum-Gallium-Nitride Semiconductors Over Entire Range of Alloy Compositions (from GaN to AlN) (2002)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

Large, high-quality bulk single crystals of AlGaN alloys have not yet been grown. Therefore, electronic bandgaps have been inferred from thin-film samples. However AlGaN films – the building blocks of the most advanced high-power microwave semiconductor devices -- have, of necessity, been grown on non-nitride substrates. Such films have typically been highly strained (altering the band structure) and have contained high concentrations of dislocations. Reported electronic AlGaN bandgaps typically varied from sample to sample and from research laboratory to research laboratory.

RYH scientists Dr. Qing Sun-Paduano and Dr. David Weyburne solved this conundrum by making a clever choice of epitaxial structures, by growing the structures, and then by using optical reflectivity to measure their apparent bandgaps.. Then, by thorough and careful accounting for strain effects on the bandgap, they determined the bandgaps that AlGaN alloys would have if they could (somehow) have been grown as bulk single crystals instead of thin films on lattice-mismatched substrates. This work was significant because nitride semiconductors have burgeoning important applications, e.g., high-power microwave RF devices; and semiconductor ultraviolet emitters and detectors.

#### **Reference:**

Q. S. Paduano, D. W. Weyburne, L. O. Bouthillette, and M. N. Alexander, "The Energy Band Gap of  $Al_{1-x}Ga_xN$ ," Japanese Journal of Applied Physics 41, Part 1 (2002) 1936-1940.

### **3.32 Electromagnetic Stirring in Crystal Growth of Bulk Semiconductor Alloys (2003+)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

This was one of the signal achievements in a multipronged effort that Dr. David Bliss of RYH led to create methods for growing uniform bulk alloy crystals of semiconductor alloys. Such crystals would be processed into wafers, just as with wafers of elemental semiconductors (silicon, germanium) or compound semiconductors (e.g., gallium arsenide and indium phosphide). Since device structures deposited on the wafers typically are made of semiconductor alloys (Si-Ge, In-Ga-P, for example) it would be desirable to be able to grow them on uniform alloy wafers whose compositions are chosen to control or tailor properties of thin films or device structures deposited on them (crystalline strain, for example, which affects the semiconductor bandgap).

“Uniform” is the key word. If one seeks simply to freeze an alloy from the melt – for example, indium-gallium phosphide, the metal constituents often segregate. If the crystal is “pulled,” the ratio of In to Ga varies along the length of the crystal, and key semiconductor properties -- electronic bandgap, emission & absorption wavelength, and lattice constant -- vary correspondingly. Each wafer in the boule is unique – an unacceptable situation for high-yield semiconductor device fabrication.

Early RYH efforts utilized an innovative secondary melt reservoir within the growth furnace that maintained a constant composition at the melt-crystal interface. The resulting alloy crystals were nearly uniform, but not quite uniform enough. Adding a small external rotating magnetic field during growth caused non-contact stirring action (the stirring occurs because the magnetic field couples to the electrically conducting melt through the Lorentz force). In experiments conducted at RYH, stirring markedly improved the uniformity of alloy crystals. It is now conceivable that, based on these advances, scientists will be able to fabricate substrates that nearly match the lattice constants of device materials, minimizing strain in the devices (or, alternatively, engineering the strain).

#### References:

N. Ma, D. F. Bliss, and G. W. Iseler, “Vertical gradient freezing of doped gallium-antimonide semiconductor crystals using submerged heater growth and electromagnetic stirring,” *Journal of Crystal Growth* 259 (2003) 26

G. W. Iseler and D. F. Bliss, “Growth of Uniform Crystals,” US Patent 6,849,121 (2005)

### **3.33 Theoretical studies of electromagnetic metamaterials; an “existence proof” for negative refractive index (2003-2011)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

Electromagnetic metamaterials are materials structures not found in nature whose properties are not linear combinations of the properties of their constituents (e.g., the properties may depend on structure), and can be engineered and manipulated so that they can be used in important applications. Experiments appearing to demonstrate the existence of metamaterials having effective electrical permittivity and magnetic permeability both less than zero (“double negative,” or DNG materials) -- hence negative refractive index -- generated worldwide excitement, but they also were very controversial. Many questioned whether the experiments were flawed. Chapter 1 of a widely-cited book by a celebrated researcher was titled, “Why Periodic Structures Cannot Synthesize Negative Indices of Refraction”!

RYH scientists Drs. Robert Shore and Arthur Yaghjian conducted rigorous theoretical research in which they used Maxwell’s Equations to study the propagation of electromagnetic waves through metamaterials. They focused, specifically, on metamaterials consisting of periodic arrays of small inclusions, especially arrays of small magnetodielectric spheres (spheres with appreciable electric permittivity and magnetic permeability). Their research effort progressed step by step in complexity as they solved Maxwell’s Equations for electromagnetic traveling waves with real propagation constants in one-, two- and three-dimensional arrays of electric dipoles and lossless magnetodielectric spheres, and finally for traveling waves with complex propagation constants supported by arrays of lossy magnetodielectric spheres. Each additional layer of complexity required difficult analysis and associated complicated computer programming to obtain numerical results for illustrating the theory.

The Shore-Yaghjian calculations demonstrated that when both the propagation constant and the frequency are small – i.e., when the wavelength is large compared to the spacing between inclusions -- a three-dimensional periodic array of discrete scatterers can indeed be regarded as a continuous, isotropic, homogeneous medium characterized by an effective (“bulk”) permittivity and permeability. Remarkably, the electromagnetic properties of the array medium are in general altogether different from those of the inclusions that form the array.

One of the major accomplishments of the Shore-Yaghjian research was simple algebraic expressions for the effective parameters of the array medium in terms of quantities that can be readily obtained from the solution of the dispersion equations that relate the propagation constants to the spacing between the array inclusions and to their permittivity and permeability. Drs. Shore and Yaghjian thus determined under what conditions an array behaves as a DNG medium – a negative refractive index metamaterial.

Dr. Shore and Dr. Yaghjian are Fellows of the IEEE.

## References:

R.A. Shore and A.D. Yaghjian, “*Traveling Waves on Two- and Three-Dimensional Periodic Arrays of Lossless Acoustic Monopoles, Electric Dipoles, and Magnetodielectric Spheres*,” Air Force Research Laboratory in-house report AFRL-SN-HS-TR-2006-0039, September 1, 2006. A condensed form of the report was published as R.A. Shore and A. D. Yaghjian, “Traveling waves on two- and three-dimensional periodic arrays of lossless scatterers,” *Radio Sci.*, 42, RS6S21, doi:10.1029/2007RS003647 19 December 2007.

R.A. Shore and A.D. Yaghjian, “Traveling waves on three-dimensional periodic arrays of two different alternating magnetodielectric spheres,” *IEEE Trans. Antennas Propagation* 57 (2009). 3077-3091

R.A. Shore and A.D. Yaghjian, *Complex Waves on 1D, 2D, and 3D Periodic Arrays of Lossy and Lossless Magnetodielectric Spheres*, AFRL Technical Report AFRL-RY-HS-TR-2010-0019, May 2010; revised June 2011. Articles based on this TR have been published in the journal *Radio Science*: R.A. Shore and A. D. Yaghjian, “Complex waves on periodic arrays of lossy and lossless permeable spheres: 1. Theory,” *Radio Sci.*, 47 (2012) RS2014, doi:10.1029/2011RS004859 ; “Complex waves on periodic arrays of lossy and lossless permeable spheres: 2. Numerical results,” *Radio Sci.*, 47 (2012) RS2015, doi:10.1029/2011RS004860.

A. Alù, A.D. Yaghjian, R.A. Shore, and M.C. Silveirinha, “Causal relations in the homogenization of metamaterials,” *Physical Review B*, 84 (2011) 054305.

### **3.34 First unambiguous experimental demonstration of negative refractive index in electromagnetic metamaterials (2004-2005)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

Although negative index refraction was demonstrated first by R.A. Shelby, D. R. Smith, and S. Schultz (University of California, San Diego) their experiment, as well as subsequent “confirmatory” experiments, employed illumination from a waveguide. Hence, the incident radiation was always perpendicular to the face of the metamaterial prism used to measure refractive index, and the microwave electric/magnetic field was parallel/perpendicular to the “posts” of the post-and-split-ring-resonator metamaterial.

The AFRL/RHYA team led by Dr. John Derov dispensed with these severe physical constraints. They employed microwave radiation that propagated through free space before it was incident on the metamaterial prism. The radiation exiting the prism was studied as a function of angle of

incidence, and also of polarization of the radiation (unlike research reported in preceding investigations).

Negative refractive index behavior was indeed confirmed -- but not for all experimental conditions. The refractive index was found to depend upon polarization and angle of incidence. Depending on the polarization of incident radiation, either positive or negative index behavior could be obtained.

#### References:

J. S. Derov, B. W. Turchinets, E. E. Crisman, A. J. Drehman, S. R. Best, and R. M. Wing, "Free Space Measurements of Negative Refraction With Varying Angles of Incidence," IEEE Microwave and Wireless Components Letters 15 (Sept 2005) 567.

J. S. Derov, B. W. Turchinets, E. E. Crisman, A. J. Drehman, and S. R. Best, "Measured Polarization Response of Negative Index Metamaterial," Proc. ICECom, Dubrovnik, Oct 2005.

J. S. Derov, B. Turchinets, E. E. Crisman, A. J. Drehman, and R. Wing, "Negative index metamaterial for selective angular separation of microwaves by polarization," Proc. IEEE Antennas and Propagation Society International Symposium, vol. 4, pp. 3753-3756 (2004).

### **3.35 First use of electromagnetic metamaterials to shape an antenna radiation pattern (2005)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

This work was the first demonstration that metamaterials can be employed to modify field geometries, not merely to change microwave circuit parameters or create gradient lenses. In this research, RYHA researchers placed a dipole antenna -- whose radiation is ordinarily isotropic in the plane perpendicular to the antenna -- either beside or between sheets of metamaterial whose index of refraction (absolute value) was nearly zero. The resulting beams were substantially collimated in the plane perpendicular to the metamaterial sheets. (This experiment can be thought of as being the inverse of total internal reflection.)

#### References:

B. W. Turchinets, J. S. Derov, S. R. Best, E. E. Crisman, A. J. Drehman, J. P. Kenney and R. P. DiMasi, "Experimental Use of Metamaterial as an Antenna Collimator," Proceedings of Antenna Applications Symposium, Allerton, IL, Sept. 2005

B. Turchinets, J. Derov, and E. Crisman, U. S. Patent 7,324,065 B2 (Jan. 29, 2008), “Antenna Radiation Collimator Structure,”

### **3.36 Method for matching electrically small antennas to 50-ohm coaxial lines (2005)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

*Electrically small antennas* have dimensions that are small compared to the wavelength of their radiation (cell phone antennas are electrically small, for example). One of the limitations of such antennas was that they had very small input resistances – typically a few ohms. Since they are usually driven by 50-ohm coaxial lines, there were extremely large reflection losses at the antenna-coax connection -- until Dr. Edward Altshuler’s research.

In order to transfer power efficiently to the antenna, an external impedance-matching circuit was required. Dr. Altshuler (RYHA) showed that, by inserting an internal matching post near the input of the antenna, the input resistance could be increased to approximately 50 ohms, thereby eliminating the need for further matching. This achievement was termed a kind of “holy grail” of antenna technology.

For his contributions to antenna theory, Dr. Altshuler received the IEEE Harry Diamond Award; he is a Fellow of the IEEE and an AFRL Fellow.

#### Reference:

E. E. Altshuler, “A method for matching an antenna having a small radiation resistance to a 50-ohm coaxial line,” IEEE Transactions on Antennas and Propagation, 53 (2005) 3086-3089.

### **3.37 Simple, accurate formulas for bandwidth and quality factor of antennas at any frequency (2005)**

#### **IN-HOUSE RESEARCH ACHIEVEMENT**

This work quickly provided a standard technique for antenna engineers to calculate antenna bandwidth and quality factor Q. The formulas apply to antennas that contain metamaterials as well as to natural materials.

Dr. Yaghjian and Dr. Best are Fellows of the IEEE.

### Reference:

A. D. Yaghjian and S. R. Best, "Impedance, bandwidth, and Q of antennas," IEEE Transactions on Antennas and Propagation 53 (2005) 1298-1324

## **3.38 Geodesic Dome Phased Array Antenna (2005+)**

### IN-HOUSE RESEARCH ACHIEVEMENT, WITH CONTRACTOR COLLABORATIONS

The GDPAA concept was invented by Dr. Boris Tomasic, AFRL/RHYA, in response to the impending need (conveyed by Dr. Shiang Liu of Aerospace Corporation) for markedly greater capacity in the AF Satellite Control Network (AFSCN). After exhaustive analysis, Dr. Tomasic concluded that the most effective solution for AFSCN would be to employ array antennas that are arranged in a quasi-hemispherical shape -- similar to Buckminster Fuller's geodesic dome (hence, the name Geodesic Dome Phased Array Antenna, or GDPAA). Each face of the dome would contain antenna subarrays. GDPAA would replace AFSCN's reflector antennas, and upgrade the entire system.

By selectively turning subarrays on or off, or in certain situations by electronically steering subarray beams, GDPAA can provide horizon-to-horizon hemispherical coverage without the mechanical steering required for reflector antennas. Because GDPAA consists of subarrays, it can be serviced in real time without having to be taken off-line -- a major operational advantage over reflector antennas. The overall performance would result in a fourfold increase in the number of satellites that AFSCN could track, with improved reliability & maintainability.

Following a successful Critical Experiment, a tracking demonstration at the NASA Wallops Island facility, GDPAA was commissioned as an Advanced Technology Demonstration (ATD). Through the ATD, it was transitioned to the Air Force Space Command (AFSPC). The ATD was managed by AFRL/RYZ, Wright Patterson AFB, assisted by technical advice from RYHA S&Es Dr. Boris Tomasic, Mr. John Turtle, and Mr. Gary Scalzi, as well as Dr. Shiang Liu of Aerospace Corporation.

At the time RYH was relocated to Wright Patterson AFB, AFSPC had not decided whether to make the investments that would be required to make GDPAA operational.

Dr. Tomasic is an AFRL Fellow.

Dr. Tomasic is the Air Force nominee for the DoD 2012 Distinguished Civilian Service Award; when this report went to press, the DoD-wide Award winner had not been selected.

## References:

B. Tomasic, J. Turtle and S. Liu, "The Geodesic Sphere Phased Array Antenna for Satellite Communications and Air/Space Surveillance - Part1," AFRL In-house Technical Report, AFRL-SN-HS-TR-2004-031, Jan 2004 .

B. Tomasic, J. Turtle, and S. Liu, "Spherical Arrays – Design Considerations," Proc. ICECom (18<sup>th</sup> Int'l Conf on Applied Electromagnetics & Communications,) Dubrovnik, Croatia, Oct 2005;

M. Henderson, M. B. Davis, and M. Huisjen, "GDPAA Advanced Technology Demonstration Overview and Results," Proc. 2010 IEEE Int'l Symposium on Phased Array Systems and Technology, Oct. 2010, pp. 140-143

B. Thompson, "Geodesic Dome Phased-Array Antenna Demonstrates TT and C Capacity" *Space War*, Feb 9, 2010

[http://www.spacewar.com/reports/Geodesic\\_Dome\\_Phased\\_Array\\_Antenna\\_Demonstrates\\_TT\\_and\\_C\\_Capacity\\_999.html](http://www.spacewar.com/reports/Geodesic_Dome_Phased_Array_Antenna_Demonstrates_TT_and_C_Capacity_999.html)

Randy L. Haupt, *Antenna Arrays: A Computational Approach*, J.W. Wiley – IEEE publishers (2010) pp. 317-322 [A photo of the GDPAA section used for the GDPAA ATD is on the front cover of this textbook]

## **3.39 First Orientation-Patterned (Quasi-Phasematched) Gallium Arsenide Structures suitable for laser applications (2005+)**

### IN-HOUSE RESEARCH ACHIEVEMENT

The objective of this research was to create an optically pumped laser host that produces tunable high-intensity light at mid-infrared and long-wave-infrared wavelengths. Since compact high-power laser hosts for such wavelengths were not then available, nonlinear frequency conversion for optical parametric oscillation was investigated.

Conventional nonlinear optical frequency conversion – e.g., frequency doubling -- requires high-intensity illumination of single crystals that are oriented so that light at the fundamental frequency  $f_1$  and light at the converted frequency  $f_2$  pass along special orientations such that the refractive index (hence the speed of light within the crystal) is the same for beams  $f_1$  and  $f_2$ . If the speeds of light for  $f_1$  and  $f_2$  differ, their beams can get out of phase and interfere destructively, resulting in low-efficiency frequency conversion.

Quasi-phasematched (QPM) structures are designed to avoid this difficulty by engineering periodic reversals of the electro-optic vector along the direction of light propagation. If light at frequency  $f_1$  moves faster than light at frequency  $f_2$  in one region,  $f_1$  moves more slowly than  $f_2$

in the next region the light traverses, so that f1 and f2 have the same *average* speed across the two regions (or 2N regions, if there are N pairs). f1 and f2 therefore exit the crystal in phase. QPM was first achieved experimentally in a Stanford University-AFRL/RYP (Wright Patterson AFB) collaboration in which ferroelectric lithium niobate was employed as the laser host. Periodic reversals of the electro-optic coefficient were created by electrostatically poling alternating strips of the lithium niobate.

Lithium niobate is transparent from visible wavelengths only up to about 5 micrometers. For infrared countermeasure applications, gallium arsenide (GaAs) is more desirable, since it is transparent for wavelengths up to 10-12 micrometers. However, since GaAs cannot be poled, periodic reversals of the electro-optic vector must be achieved by engineering the crystal growth in such a way that the crystal structure reverses periodically along the direction of light propagation. Stanford University researchers created orientation-patterned GaAs (OP-GaAs) via an ingenious molecular beam epitaxy (MBE) thin film growth technique.

To achieve the high laser powers needed for infrared countermeasures (IRCM) applications, the QPM films should be at least 1 mm (1000 micrometers) thick. However, MBE-grown film thicknesses rarely exceed 10 micrometers. The Stanford films therefore were used as templates on which thick OP-GaAs device films were grown (this was understood from the outset). Dr. Howard Schlossberg of the Air Force Office of Scientific Research (AFOSR) enlisted RYP materials scientists who possessed the appropriate expertise; together, they initiated an AFOSR-sponsored research Task.

The requisite high-quality thick films having stripes of alternating crystallographic orientation had never been successfully fabricated. High-tech epitaxial growth is almost always designed to produce layers whose planes are perpendicular to the growth direction – somewhat like a layer cake; OP-GaAs was like producing a layer cake turned on its side.

RYP scientists – especially Drs. Candace Lynch, David Bliss, and David Weyburne, designed and built low-pressure hydride vapor phase epitaxy (HVPE) growth furnaces and associated equipment in which they ultimately were able to grow 1-mm-thick laser-quality OP-GaAs materials in 10-12 hours -- a crystal growth *tour de force*. Samples having different stripe widths were grown, from which optical parametric amplifiers (OPOs) covering different wavelength bands (from mid-wave infrared to terahertz) were fabricated. The HVPE process was transferred to BAE Systems, Nashua, NH.

At the time when RYP was relocated to Wright Patterson AFB, per the 2005 BRAC, RYP scientists had begun a follow-on program for growing thick QPM films of gallium phosphide (GaP). GaP has an even wider visible/infrared transmission window than GaAs, and has superior optical absorption properties.

For her contributions to this achievement, Dr. Candace Lynch won the 2010 Air Force Harold Brown Award -- the highest Air Force R&D award -- which was presented by the Secretary of the Air Force.

## References:

D. F. Bliss, C. Lynch, D. Weyburne, K. O'Hearn, and J. S. Bailey, "Epitaxial Growth of Thick GaAs on Orientation-Patterned Wafers for Nonlinear Optical Applications," *Journal of Crystal Growth* 287 (2006) 673-678

R. D. Peterson, D. Bliss, C. Lynch, and D. Tomich, "Progress in orientation-patterned GaAs for next-generation nonlinear optical devices," *SPIE Proceedings* 6875 (2008) 68750D-1

C. Lynch, D. F. Bliss, T. Zens, A. Lin, J. S. Harris, P. S. Kuo, and M. M. Fejer, "Growth of mm-thick orientation-patterned GaAs for IR and THZ generation," *J. Cryst Growth* 310 (2008) 5241-5247

P. Kuo, "Thick OP-GaAs for Nonlinear Frequency Conversion," PhD Thesis, Stanford University, March 2008. [Contains a historical summary of the growth of OP-GaAs materials]

## **3.40 First supergain electrically small antennas (2008)**

### IN-HOUSE RESEARCH ACHIEVEMENT

By using resonant array elements, RYHA researchers created a means of building "electrically small" supergain antennas. This achievement opens the possibility of creating practical electrically small antennas that have both increased gain and multiple resonances

## References:

A.D. Yaghjian, T. H. O'Donnell, E. E. Altshuler, and S. R. Best, "Electrically small supergain end-fire arrays," *Radio Science* 43 (2008) RS3002.

A.D. Yaghjian, T. H. O'Donnell, E. E. Altshuler, and S. R. Best, U.S. Patent 8,134,516 B1 (Mar 13, 2012), "Electrically Small Supergain Endfire Array Antenna"

## 4.0 About the Author:

Michael N. Alexander earned his A.B. *cum laude* in physics at Harvard (1962) and his Ph.D. in physics at Cornell (1967). From 1967-1978 he was a Research Physicist at the Army Materials & Mechanics Research Center, Watertown, MA (later merged into the Army Research Laboratory), using nuclear magnetic resonance to conduct basic research in semiconductors, metals & alloys, ceramics, and polymers. From 1978-1986 he was a Senior Member of Technical Staff at GTE Laboratories, Waltham, MA, where he conducted basic and applied research on phosphors and glasses for lighting products, gallium arsenide semiconductors, and silicon radiofrequency power devices. During 1986-1988 he was a Principal Scientist at Thermo Electron (now Thermo Fisher) Corp., Waltham, MA conducting and leading research on high-temperature thermoelectrics, and supervising development of thermoelectric power modules for the SP-100 nuclear-powered 100 kilowatt space-borne power generation system that NASA was developing for DoD.

In 1988 Dr. Alexander joined the USAF Rome Air Development Center (later, USAF Rome Laboratory) at Hanscom AFB, MA, becoming Chief of its Electromagnetic Materials Technology Division, supervising basic and applied research (6.1 and 6.2) on materials for electronic and photonic devices. The Division was among world leaders in semiconductor and (opto)electronics research. Its “Advanced Electromagnetic Materials” Team attained and maintained coveted AFOSR “STAR Team” status for nine years. Dr. Alexander received the 1995 Major General Daniel Doubleday Award given for “distinguished contributions to the effective management of the Air Force Rome Laboratory.” For three years he chaired the Electronic Materials Subpanel of the OSD Project Reliance Technical Panel on Electron Devices, leading tri-service and agency teams that appraised military R&D on electronic materials at OSD’s annual Technical Area Review and Assessments (TARAs).

Subsequent to creation of the AF Research Laboratory (1997), Dr. Alexander’s group became the Electromagnetic Materials Branch, Electromagnetics Technology Division, AFRL Sensors Directorate. After a reorganization in which his Branch was disbanded (2002), he became Technical Advisor of the Sensors Directorate Electromagnetics Technology Division (AFRL/RYP) – technical lead for approximately 150 government and on-site contract researchers who conducted primarily 6.1 and 6.2 research on electronic materials, optoelectronic devices, infrared components and techniques, RF devices and components, antenna theory and components, electromagnetic scattering, and signal/image processing. He retired in August 2011, when RYP relocated from Hanscom AFB to Wright Patterson AFB per the 2005 BRAC.

Dr. Alexander has authored or co-authored approximately 45 technical journal articles and book chapters; he holds 10 U.S. Patents. He has been an invited lecturer at professional meetings and at university, industrial, and government laboratories.

## 5.0 APPENDIX - Electromagnetics Technology Division Patents

This is a partial list of patents generated by Electromagnetics Technology Division employees from about 1988 to 2012. All patents awarded between Jan 1997 to Oct 2011 are included. We believe we have complete lists for RYHC and RYHX for 1990-1997. However, many patents awarded to AFRL/RYHE (Electromagnetic Scattering and Phenomenology Branch) and AFRL/RYHI (Infrared Sensor Technology Branch) inventors between 1988 and Jan 1997 were not available for inclusion.

J. A. Adamski, U.S. Patent 4,764,350 (16 Aug 1988), "Method and Apparatus for Synthesizing a Single Crystal of Indium Phosphide."

J. A. Adamski and B. S. Ahern, U.S. Patent 4,783,320 (8 Nov 1988), "Rapid Synthesis of InP."

B. S. Ahern and D. W. Weyburne, U.S. Patent 4,864,575 (5 Sep 1989), "Static Periodic Field Device for Free Electron Laser."

B. S. Ahern and D. W. Weyburne, U.S. Patent 4,916,356 (10 Apr 1990), "High Emissivity Cold Cathode Ultrastructure"

B. S. Ahern, R. M. Hilton, G. W. Iseler, U.S. Patent 4,963,334 (16 Oct 1990), "High Temperature Heat Pipe Coracle and Process."

B. S. Ahern, U.S. Patent 5,040,336 (20 Aug 1991), "Non-Contact Polishing."

B. S. Ahern and D. W. Weyburne, U.S. Patent 5,129,360 (14 Jul 1992), "Actively Cooled Effusion Cell for Chemical Vapor Deposition."

B. S. Ahern and D. W. Weyburne, U.S. Patent 5,136,978 (11 Aug 1992), "Heat Pipe Susceptor for Epitaxy."

B. S. Ahern and D. W. Weyburne, U.S. Patent 5,252,366 (12 Oct 1993), "Chemical Vapor Deposition Method Using an Actively Cooled Effuser to Coat a Substrate Having a Heated Surface Layer."

B. S. Ahern, D. W. Weyburne, G. W. Iseler, H. R. Clark, U.S. Patent 5,387,331 (7 Feb 1995), "Wafer-Cutting Device."

M. N. Alexander, U.S. Patent 5,760,327 (2 Jun 1998), "Superconducting Radar Decoys and Camouflage."

M. N. Alexander, U.S. Patent 6,306,739 (23 Oct 2001), "Method and apparatus for depositing thin films of group III nitrides and other films and devices made therefrom."

E. E. Altshuler, U. S. Patent 5,289,198 (Feb 22, 1994), "Double-Folded Monopole"

E. E. Altshuler and D. S. Linden, U.S. Patent 5,719,794 (Feb 1998), "A Process for the Design of Antennas using Genetic Algorithms."

A.F. Anwar and R. T. Webster, U.S. Patent 7,485,908 (3 Feb 2009), "Insulated gate silicon nanowire transistor and method of manufacture."

A.F. Anwar and R. T. Webster, U.S. Patent 7,700,419 (20 Apr 2010), "Insulated gate silicon nanowire transistor and method of manufacture."

A. F. Armington and J. J. Larkin, U.S. Patent 4,576,808 (18 Mar 1986), "Quartz Growth on X-Seeds."

S. Bachowski, B. S. Ahern, R. M. Hilton, J. A. Adamski, U.S. Patent 5,252,175 (12 Oct 1993), "Capillary Pressure Relief for Magnetic Kyropoulos Growth of Semiconductor Crystals."

S. Bachowski, D. F. Bliss and R. M. Hilton, U.S. Patent 5,431,125 (11 Jul 1995), "Twin/Free Crystal Growth of III/V Semiconductor Material."

B. R. Bennett, J. P. Lorenzo, and K. Vaccaro, U.S. Patent 4,900,591 (13 Feb 1990), "Method for the deposition of high quality silicon dioxide at low temperature."

D. F. Bliss, R. M. Hilton, J. A. Adamski, U.S. Patent 5,493,985 (27 Feb 1996), "Process and Apparatus for Controlled Synthesis and In-Situ Single Crystal Growth of Phosphorous Compounds and the Crystals Therefrom."

D. F. Bliss and H. E. Bates, U.S. Patent 5,543,360 (6 Aug 1996), "Bicrystal Sapphire Ribbon Substrate for High Tc Superconductor Devices."

D. F. Bliss, G. Bryant, D. Gabbe, U.S. Patent 5,656,079 (12 Aug 1997), "Apparatus for the synthesis and growth of single crystals of phosphorus compounds."

D. F. Bliss, B. G. Demczyk, J. Bailey, U.S. Patent 6,143,070 (7 Nov 2000), "Silicon-germanium bulk alloy growth by liquid encapsulated zone melting."

D. F. Bliss, V. L. Tassev, M. J. Sucavage, J. S. Bailey, U.S. Patent 6,969,426 (29 Nov 2005), "Forming improved metal nitrides."

J. A. Cappelli, L. F. Lowe, S. D. Mittleman, U.S. Patent 5,120,967 (9 June 1992), "Apparatus for direct measurement of dose enhancement."

H. R. Clark, Jr., G. W. Iseler, B. S. Ahern, et al, U.S. Patent 5,327,625 (12 Jul 1994), "Apparatus for forming nanometric features on surfaces."

H. R. Clark, Jr., G. W. Iseler, B. S. Ahern, U.S. Patent 5,512,808 (30 Apr 1996), "Method and Apparatus for Forming Nanometric Features on Surfaces."

H. R. Clark, Jr and B. S. Ahern, U.S. Patent 5,690,807 (25 Nov 1997), "Method for Producing Semiconductor Particles."

E. E. Crisman, U.S. Patent 7,002,673 (21 Feb 2006), "Optical strain gage compatible with fiber optic systems."

E. E. Crisman, U.S. Patent 7,324,001 (29 Jan 2008), "System and Method for Detecting and Discriminating Between Water and Ice Formation on Objects."

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