

Women in Engineering and Science

Alice Cline Parker
Leda Lunardi *Editors*

Women in Microelectronics

 Springer

Women in Engineering and Science

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Women in Microelectronics

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“To our children”

Foreword

This unique book captures the stories and perspectives of pioneering women in microelectronics, providing insight into the technical and personal challenges they faced, and how they were able to overcome these to succeed. It is our hope that these role models will encourage and inspire the next generation of bold, innovative engineers to shape a brighter future for all.

Dr. France Córdova, former Director of the U.S. National Science Foundation, wrote “Diversity—of thought, perspective, and experience—is essential for excellence in research and innovation in science and engineering.” This is because diverse teams comprise a wider range of viewpoints and skill sets, i.e., greater collective intelligence. Women should benefit from engineering innovations as much as men. For these reasons, it is important for women to be included in engineering teams to develop better solutions and improve the quality of life for all members of our society.

Engineers continually innovate new processes, devices, and systems to solve problems and improve the quality of life. Perhaps the most prominent example of this is the steady advancement of microelectronics technology over the past 60 years that sustained an exponential pace of performance improvement in information processing, communication, and storage. Indeed, the information technology revolution has had a transformative impact on every aspect of life in modern society.

The confluence of cloud computing, big data, artificial intelligence, and the Internet of Things today is projected to give rise to digital transformation in all sectors of the economy. This vision of the future cannot be realized without new innovations, however, due to the physical limits of transistor miniaturization and fundamental energy efficiency limits of digital computing. It is widely recognized that new electronic materials, manufacturing processes, logic and memory devices, integrated circuit chip architectures, etc. will be needed to circumvent these limitations.

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Chapter 1

Introduction



Alice Cline Parker and Leda Lunardi

1.1 Scope

Electrical engineering was essentially born in the twentieth century, with women involved from the beginning, if you set aside Ben Franklin's experiments with kites, lightning rods, and electricity two centuries earlier, and observations about charge and electricity dating back to the ancient Greeks. Edith Clarke, considered the first professional woman electrical engineer, analyzed electrical power systems and Margaret Mary Partridge, also an electrical engineer, began involving and supporting women in engineering. Women entered the engineering profession in unorthodox ways, exemplified by actress Hedy Lamarr, who made major contributions to communication theory during World War II. Kitty O'Brien Joyner began as an electrical engineer, but made major contributions to aeronautics and flight during her long career with NASA. Another electrical engineer, Thelma Estrin, had a long and distinguished career in the field of biomedical engineering.

The first point-contact transistor was invented at Bell Labs in 1947, and from that humble beginning of the golden age in microelectronics to what has been an engineering revolution, women have been involved. Now, we open car doors,

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communicate, preserve virtually every moment of our lives, and know who is at the front door when we are thousands of miles away. Very few women were part of the microelectronics revolution that has moved us from the industrial age to the information age. As more women are entering the microelectronics field, it is important to preserve the history of early pioneers, to understand and celebrate the challenges these women have overcome, to inspire young women, and to raise awareness of contributions.

Mildred Dresselhaus, Institute Professor at Massachusetts Institute of Technology, inspired electrical engineers with her accomplishments on electronic properties of materials. The VLSI (very large-scale integration) revolution that provided a design approach to today's integrated circuit chips was led by Lynn Conway, along with Carver Mead, California Institute of Technology Professor. Mead's former doctoral student, Misha Mahowald, along with Mead, triggered the current wave of activity in neuromorphic computing, modeling the brain with electronics.

What is the combination of traits and circumstances that motivated these women to succeed in engineering? We, the editors, have assembled some chapters describing women's journeys and career paths related to microelectronics and beyond. Along with documenting what it took to succeed, we hope that the paths followed will inspire young women in this field, and give them courage to persist and succeed. This book contains stories of women engineers' paths through the golden age of microelectronics.

These stories, like the biographies of Marie Curie and the National Geographic's stories of Jane Goodall's research that inspired the authors, will inspire and guide young women along unconventional pathways to contributions that we can only begin to imagine. The reasons and how the women contributors here chose their career paths and how they navigated their careers will be of interest to anyone, from university advisors to industry Chief Executive Officers, who can imagine the advantages of a future with a diverse workforce. One word that comes to mind when editing this book is "unconventional."

The book will help managers and industry leaders to understand the environment these women not only survived, and persisted, but also blossomed in, to enlighten future decision makers. It will inspire young women to pursue unconventional careers. The stories in this book are timeless. A century from now, the chapters will contain stories told by some brave pioneers at the beginnings of a new age.

1.2 Chapter Introductions by Author

Susan Palmateer: “From Crystal Growth to New Product Introduction”



Only in the late 1970s, compound semiconductor epitaxy technologies were developed enabling the precise control of the different doping levels and the thickness of each layer, “band gap engineering”. With more advances in the bulk crystal growth and diverse epitaxial growth techniques, it rapidly expanded the field for compound semiconductor applications. In the field of communications, electronic devices with wider bandwidth and lower noise were one of them: radio transmission and detection including radar equipment as well as commercial systems.

Dr. Palmateer, who started as a compound semiconductor materials grower moving through different paths, tells her journey on becoming a group leader in industry and what it took.

Adrienne Stiff-Roberts: “Thin-Film Deposition of Hybrid Materials”



Conventional semiconductors (silicon, germanium) are commonly found in nature as crystals. Compound semiconductors like gallium arsenide (GaAs) or indium phosphide (InP) are “manufactured” in controlled conditions in a laboratory. New techniques have been investigated to create hybrid materials comprised of organic and inorganic components primarily for optoelectronic device applications, such as infrared photodetectors, photovoltaic solar cells, light-emitting diodes, and sensors.

Prof. Stiff-Roberts presents her research on resonant infrared matrix-assisted pulsed laser evaporation for the thin-film deposition of hybrid materials.

One of the challenges of the research is to control the co-deposition of two or more materials with different chemical and physical properties in order that the synthesis has pre-determined properties and functionality.

Missing Santosh Kurinec.

Santosh Kurinec: “Nanoscale Materials Engineering for Microelectronics”



Prof. Kurinec, a multidisciplinary expert on magnetic, optical, and electronic materials, tells her journey how to conduct a world class research on integrating novel materials and devices onto CMOS platform for heterogeneous integration. With her students, she required inter-disciplinary, inter-institutional, and global collaborations.

Zeynep Çelik-Butler: “Smart Skin: Multifunctional, Flexible, Conformable Sensor Arrays”



The evolution of electronic devices and their integration enabled the development of applications that required to conform to different surfaces. Large areas and flexible electronics have been researched for data processing, specifically in the areas of decision making, biochemical sensing, and energy harvesting.

Prof. Çelik-Butler reviews her career in a chapter dedicated to the topic of Smart Skin, a term defined to mimic the human skin, that is extensively applied to robotics.

Xiuling Li: “Nanodevices and Applications: My Nonlinear Career Trajectory”



An important aspect in microelectronic devices is the course taken from the concept, the device structure and fabrication development. The magic behind different approaches and processing steps is a multi-disciplinary task, requiring critical decisions that lead to further integration and applications.

Through her career in industry and academia, Dr. Li has processed 3D structures and devices with bottom-up growth and top-down fabrication that led to numerous applications in the disciplines of electronics, photonics, nanotechnology, and quantum technology.

Ru Huang: “Gate-All-Around Silicon Nanowire Transistor Technology”

Prof. Huang has been exploring the fundamental limits of scaling field effect transistors by investigating vertical nanowire transistors with all-around gate geometrics for an optimum field effect control of the channel carriers.

Dr. Huang presents her chapter on silicon-based transistors research including the gate-all-around design to enhance the conductivity while easing the ohmic contact formation.

Leda Lunardi: “Heterojunction Bipolar Transistors and Monolithically Integrated Photoreceivers Among Other Applications”

Incorporation of a wide bandgap emitter was proposed by Schockley in 1951 and Kroemer in 1957; however, it took almost two decades in the development of optimum growth conditions and epitaxial material technology for compound semiconductors to unleash the potential of heterojunction bipolar transistors.

Prof. Lunardi reviews her contributions on two compound semiconductors heterojunction bipolar transistor technologies: GaAs and InP, specifically in the development of photoreceivers for optical communication applications.

Mona Zhagoul: “Integrated Circuits, MEMS, and Nano Electronics for Sensors Applications”

Prof. Zhagoul started her career as a circuit designer. As soon as she had an opportunity to learn CMOS, she employed it in analog and digital applications. Over the years, she has incorporated sensors in her circuits using PZT as the piezoelectric material, and temperature sensors using thermocouple techniques developing chemical and gas sensors. By using microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS), she has been able to expand the range of applications to power sensors and micromachined accelerometers. Her more recent interest includes synthesis of 2D materials and their inclusion in the design of electronic circuits.

Rhonda Franklin: “From Microwave Communication Systems to Nanomedicine Tools: Using Advanced Microelectronics Fabrication as an Enabler”



Prof. Franklin started her career in the microwave space communications with focus on interconnect technology. She developed nanofabrication methods for circuits and devices, and characterization techniques in order to understand electric/magnetic materials. She developed techniques for reducing electric field and crosstalk on transmission lines and other passive components at the wafer-level of unpackaged circuits.

Dr. Franklin employs nanofabrication techniques into cells as biomarkers for cancer research.

Jennifer Hasler: “Becoming a Creative Female Engineer ... Enabling the Next Computing Opportunities”



Prof. Hasler tells her creative and personal story, starting and becoming an electrical engineer. She recalls the details of discovery on her research trajectory and working on the cutting edge of computation and neuromorphic techniques, and then becoming a female engineer.

Alice Parker: “From Silicon to the Brain Using Microelectronics as a Bridge”



The research journey of Alice Cline Parker is presented in this chapter. Alice Parker’s family background and the circumstances that propelled her into engineering begin the chapter. The journey her research took from a more-conventional electrical engineer into the neuroscience-inspired world of neuromorphic circuits completes the chapter. The role of nanotechnology in her research directions is also highlighted. Parker cites the individuals who were key to her career success, beginning with her father’s influence.

Telle Whitney; “VLSI and Beyond: The Dream of Impact, Creating Technology with Inclusive Cultures”



Telle Whitney describes her path from her early days in Salt Lake City to becoming CEO of the Anita Borg Institute, creating and leading the organization to one of global impact, with a reach of over 750 K technical women. In the field of VLSI design, Telle was a trailblazer, both in the early days of the VLSI revolution and as an entrepreneur in the semiconductor field. She is a recognized leader both as a semiconductor pioneer and as award-winning leader in the movement for women creating technology that impacts everyone’s life.

Gabriele Saucier: “Creating Collaborative Design Environments”



This chapter relates the journey of a girl born in a remote European region under war and who had little chance for accessing engineering study, but who obstinately wanted to learn, understand the world around her, and “participate”.

From PHD to a university professor position, from logic design to real circuit layout and ultimately to web-based silicon IP exchange, she met obstacles as a mother and a woman but also got support from the IEEE community, from EU projects, and nice people that she had a chance to meet in her life.

I wish to all women of the world to be as obstinate as I was (and even more) to learn, understand and participate in their world which may not be an easy one ...

Diana Marculescu: “The Quest for Energy Aware Computing: Confessions of an Accidental Engineer”



Dr. Marculescu’s contributions to microelectronics started with electronic design automation tools. With her computer science skills and expanding emerging platforms, she has incorporated into design parameters related to power consumption, reliability, and the nanoscale semiconductor.

Lauren Palmateer: “Semiconductors to Light Antennas: A Woman Engineer’s Career at the Turn of the Third Millennium”



Starting with an earlier technical internship in cosmology and following her sister’s path to engineering school, Dr. Palmateer completed her studies with a graduate degree on III–V heterojunction field effect transistors. After graduate school, her industrial career continued in different areas including thin-film transistors and reflective displays.

In her chapter, Dr. Lauren Palmateer gives a candid account of her continuous learning journey as a world traveler.

1.3 Epilogue: Changes and Rising Stars

The last decade has seen a blossoming of interest in careers in engineering, science, and technology, particularly for women. Notable in the maker space is AdaFruit Industries founder Limor Fried. Jeri Ellsworth has blazed trails as an electronic gaming entrepreneur. Entrepreneur Courtney Gras is inspiring student entrepreneurship, and fellow electrical engineer Christina Koch is an astronaut. Now the women of electrical engineering are too numerous to mention, even in the microelectronics domain. Recognition by professional societies and other organizations has highlighted many of these women following in the footsteps of the pioneers included here.

At the time of this book printing, 50% of freshmen at USC in the Viterbi School of Engineering and 50% of freshmen in the College of Engineering at NC State are women. We are looking forward to the coming decades when women in microelectronics will be the norm, not the exception. As you explore the chapters that follow, note the exceptional circumstances and persistence that led these women to careers in microelectronics. If you are an academician or industry leader supporting the advancement of women in engineering, these chapters might give a better understanding of the challenges faced. If you are an aspiring engineer, the editors hope you will find inspiration, support, and encouragement from reading these engineers’ journeys.

Chapter 2

From Crystal Growth to New Product Introduction



Susan Palmateer

2.1 The Impact of Diversity, Mentoring, Networking, and Teamwork on My Leadership Journey

I was born on July 2, 1957, in New Jersey to Helen L. Palmateer and George R. Palmateer. I spent my early years in Fort Lee, New Jersey, and I remember Palisades Amusement Park where I enjoyed many weekends with my family. I moved to Norwood, New Jersey, when I was 5 years old with my family and younger sister Lauren Fay Palmateer—another engineer with a Ph.D. in electrical engineering from Cornell University.

Now that's interesting—two female engineers with Ph.D.s!

How did we both end up with Ph.D.s from Cornell? We had great mentors and encouragement from our parents. At a young age, teachers like Mr. Skorka, Ms. Besold, and Ms. Sovolus saw our potential in math and science and brought it out. In high school, our role models and mentors were great too—Mr. Kimball, Ms. Kelly, Mr. Wolfe, and Mr. Donofrio. The diversity and inclusion was a strong influencer growing up in New Jersey outside of Manhattan where Italians, Polish, Jews, and blue-collar and white-collar workers all came together. Did forget to mention grades kindergarten through fifth? We were in Catholic school, and while not great with academics, coaching, or mentoring, it instilled the benefit of hard work.

Therefore, off I went to Monmouth College in 1975. I had money for the first year, which was \$5000 plus scholarships. In my senior year at Monmouth, I got an internship at Bell Laboratories. It was exciting times in technology—lots of funding and some of the most renowned scientists. I had an opportunity to learn from Dr. Martin Schneider and Dr. Cho, the father of molecular beam epitaxy. I would later be known as the mother of molecular beam epitaxy.

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Now, how did my sister Lauren follow the engineering path? A little story: one day she came to visit me at Bell Labs, where she met Dr. Arno Penzias, a Nobel Prize winner at Crawford Hill where he and Dr. Robert Carlson were collecting background radiation with an antenna. Dr. Penzias came to me a few days later and asked me if my sister would be interested in a job working for him. He told me she asked him a question he was not able to answer and said, “I want to hire that woman!”

Lauren transferred to Monmouth College from SUNY Albany and got a bachelor’s degree in electrical engineering while running a telescope and collecting data for Dr. Penzias and Dr. Carlson for the next 3 years. I assume this data is what contributed to their winning a Nobel Prize for the big bang theory.

We then both went on to earn Ph.D.s from Cornell because of our mentor, Dr. Martin Schneider at Bell Laboratories. In the interim, Lauren worked for IBM as well as other large and small companies. (Read more in Lauren Palmateer’s chapter of this book.)

So, how did we both end up with PhDs in electrical engineering? It was the impact of diversity, mentoring, coaching, and networks we developed. It started with a mother who said, “You can do and be whatever you want.” She encouraged us to be independent and pursue careers so we could support ourselves and not depend on someone else. Figure 2.1 captures my leadership journey timeline with the influence of teamwork, adaptability, attitude, and diversity, overlaid on my academic and work experiences. I constructed this to talk to the next generation of women entering the engineering field.

What did I see and learn from my mentors? Drive and passion. Professor Lester Eastman, one of my graduate degree professors, was my most influential mentor. He had drive and passion, and saw no difference between men or women or minorities. He treated everyone equally. The greatest advice Professor Eastman passed on to me, and all 125 of his graduate students, was to work as a team on technology that made a difference in performance, and develop technology that could transition into products.

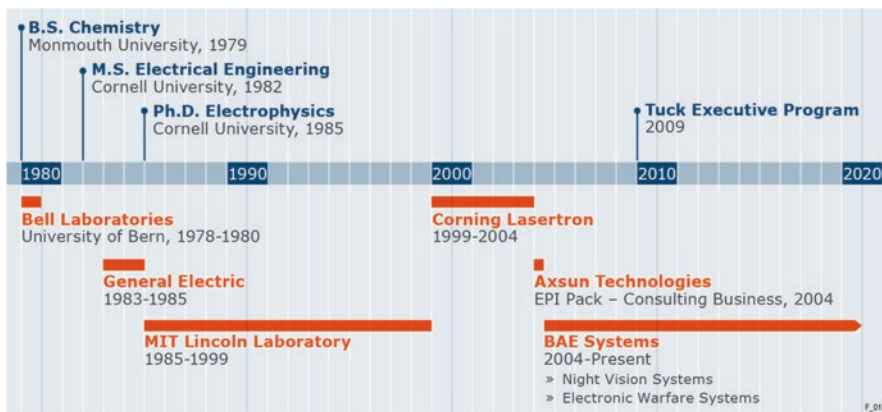


Fig. 2.1 Dr. Palmateer’s leadership journey timeline

2.2 Life Challenges and Insights

I faced a lot of adversity as a female engineering student, and early in my career.

I was approached several times with suggestive implications by influential and successful male engineers and leaders, and politely said, “No, thank you.” I was told that I’m “not as smart as the guys” by a professor and an advisor. I was also told I was “not as capable” as the men and that I “shouldn’t be here” by an advisor. I was hit on the buttocks by a research advisor, which left a hand print for 7 days, and was then told by colleagues that I “asked for it.” This was my most challenging lesson in life. I had a male colleague move all my chairs and various other lab equipment into the hallway each day to slow me down, and another say, “She won’t work again—she’s pregnant.” Not to mention the sexually suggestive items in the workplace in the 1980s.

While I don’t feel any woman should have to experience these challenges on their path to becoming an engineer, the reality is that we are often doubted and pushed outside of our comfort zones. I faced these situations with a positive attitude and used each one as an opportunity to advocate for myself and other women, in the process of learning and teaching many valuable lessons about perseverance. No one was going to get in the way of my dreams to earn a Ph.D. I tell you this so that you feel empowered to do the right thing, and be resilient in the face of adversity. Future generations of young women are counting on you to pave the way and be mentors. Together we can work to remove barriers preventing them from reaching their goals.

2.3 Crystal Growth—Molecular Beam Epitaxy, Organometallic Chemical Vapor Deposition, and Gas Source Molecular Beam Epitaxy

2.3.1 *Molecular Beam Epitaxy*

I was first introduced to molecular beam epitaxy (MBE) and III–V semiconductors at Bell Laboratories in the optical devices group in Holmdel, New Jersey, where I learned from the experts. From Bell Labs, I went off to Cornell where I did both my master’s and Ph.D. [1, 2] research in MBE and the diffusion and impurity incorporation in III–V semiconductors. The out diffusion and redistribution of substrate related impurities during MBE growth was shown to adversely affect device performance. An understanding of the diffusion mechanisms in substrates and epitaxial layers was developed to devise a way of controlling atomic movement of impurities during MBE growth. The redistribution of impurities was found to be influenced by surface electric fields and vacancies in the semiconductor [3, 4] (Fig. 2.2).

Planar doped barrier structures were shown to be extremely sensitive to MBE growth conditions specifically intrinsic doping levels (i.e., unintentional doping levels and deep levels), which can be substrate dependent. Heat treatment of Gallium



Fig. 2.2 Far above Cayuga’s Waters—Cornell University, Ithaca, NY

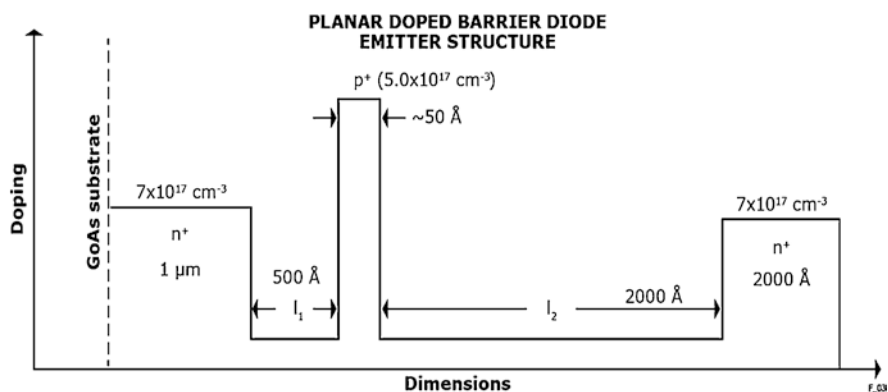


Fig. 2.3 Planar doped barrier structure [5]

Arsenide (GaAs) substrates in combination with controlling the growth conditions resulted in precise control of designed barrier heights (Fig. 2.3).

I finished my Ph.D. research at General Electric in Syracuse, New York. I was in charge of producing MBE material for high frequency and low-noise microwave devices. By pre-annealing substrates and carefully controlling the V:III flux ratio during growth, extremely high-purity GaAs and GaAs/Aluminum Gallium Arsenide (AlGaAs) quantum wells were grown. In 1985, I produced the highest mobility GaAs as shown in Fig. 2.4 and single quantum well structures as shown in Fig. 2.5 by MBE.

Critical to these successes was careful startup of the MBE system combined with understanding the growth thermodynamics-As4 flux ratio, growth temperature,

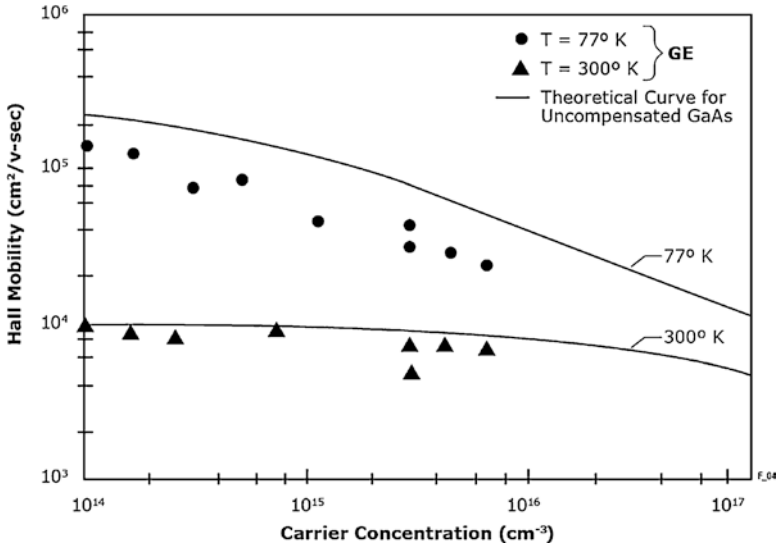


Fig. 2.4 Plot of theoretical and experimental 77K Mobility verses carrier concentration for n-type GaAs [2]

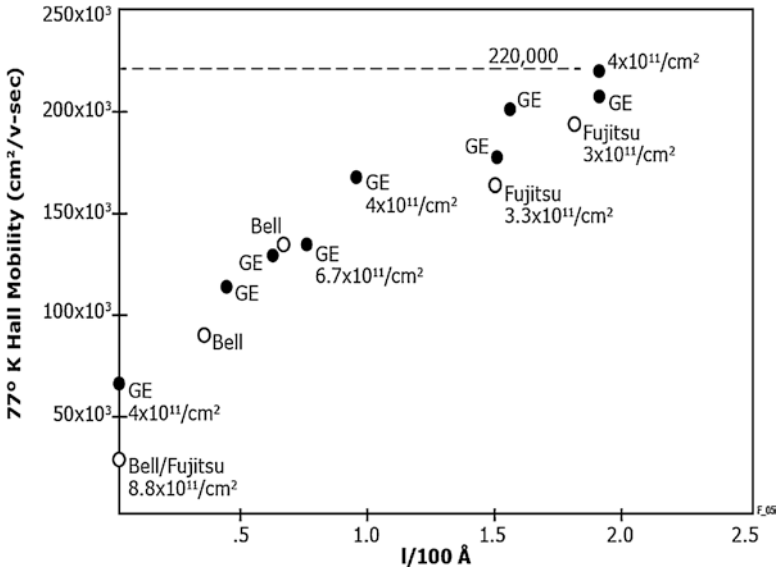


Fig. 2.5 Plot of 77K mobility versus l/100 (l = spacer layer thickness) [2]

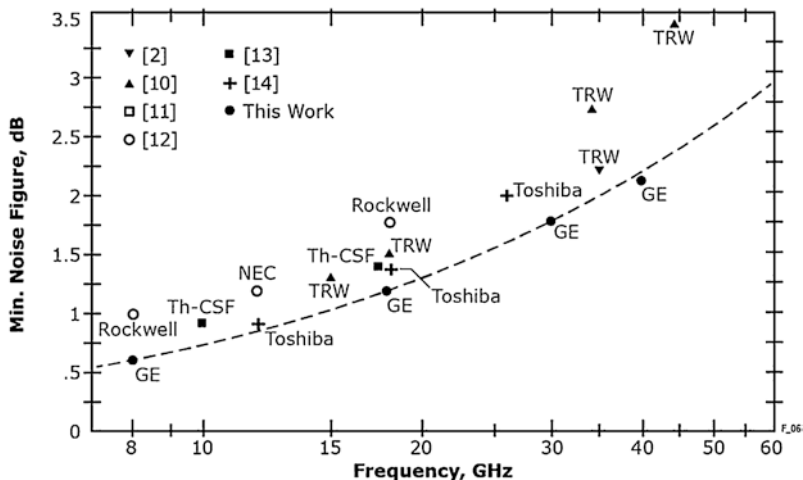


Fig. 2.6 Reported HEMT noise performance at room temperature from major laboratories [6]

impurity redistribution and thermal conversion of the growth front. My manager and mentor, Dr. James Hwang, provided the resources and coaching to successfully create this capability.

This high-purity material resulted in the lowest noise high-electron-mobility transistors ever produced with the lowest noise figure to date demonstrated in 1985 as shown in Fig. 2.6.

It was during this time at General Electric that I first developed an intense interest in process control and process variability, and my passion for transitioning technology into products.

Accomplishments and Insights

I produced the highest purity MBE material to date and set up a manufacturing infrastructure for microwave devices. What enabled me to do this was chemistry training (attention to details) and mentorship by Dr. Jim Hwang, who provided the funding, which fueled my drive and passion.

2.3.2 Organometallic Chemical Vapor Deposition

In the late 1980s at MIT Lincoln Laboratories, we (Dr. Christine Wang, Dr. Steve Groves, James Caunt, Dave Hovey, and myself) designed and built two new organometallic chemical vapor deposition (OMCVD) reactors for the growth of compound semiconductors GaAs/AlGaAs and Gallium Indium Arsenide Phosphide/Indium Phosphide (GaInAsP/InP). With gas flow visualization, tracer gas studies, and numerical modeling, these reactor designs were optimized for highly uniform,

reproducible, abrupt interface growth. High-performance laser diodes were produced in each reactor for each respective material system [7].

It was shown that convective cells might form when a gas of a different density than that of the gas already flowing in the tube is rapidly switched into the reactor, even when the run-vent lines of the switching manifold are pressure- and flow-balanced. This density effect was reported for the first time, and was found to severely degrade the material quality of InP/InGaAs and Indium Phosphide/Indium Gallium Phosphide (InP/InGaP) heterojunctions.

The above shown in Fig. 2.7 is referred to as a stagnation flow reactor designed and developed by Dr. Christine Wang and James Caunt. Tangential gas injection resulted in fully developed flow that could be made laminar by disk rotation. Gas injection through a porous plug produced the most uniform flow to the disk. In addition, gas residence times were minimized when this injection geometry was combined with low pressure. Extremely uniform GaAs and AlGaAs epilayers were grown in this vertical rotating-disk OMCVD reactor. Diode lasers were produced with threshold current densities, differential quantum efficiencies, and emission wavelengths that were highly uniform over 16 cm². Excellent wafer-to-wafer reproducibility of the emission wavelengths was demonstrated [8].

Figure 2.8 shows sulfur hexafluoride (SF₆) detected at the center of the susceptor in the stagnation flow reactor as a function of time after gas switching for different density changes. These tracer gas experiments were instrumental in designing OMCVD reactors capable of producing abrupt interfaces with excellent across wafer uniformity.

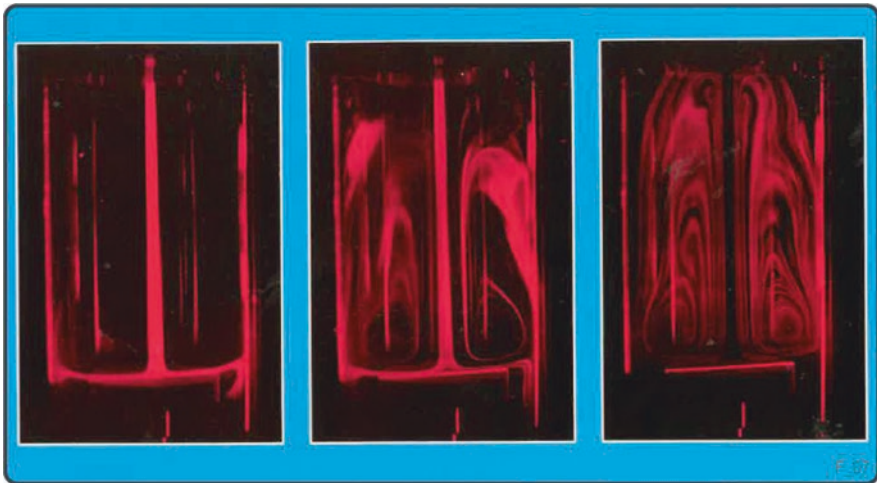


Fig. 2.7 Vertical cross sections showing flow patterns at room temperature and 1 atmosphere obtained for gas injection through a coaxial pipe inlet: (a) 1 s after initial introduction of smoke; (b) 20 s after initial introduction of smoke; (c) 1 min after smoke was turned off. Intense gas recirculation occurs throughout the reactor as a result of the impinging jet. “Provided by MIT Lincoln Laboratory” [8]

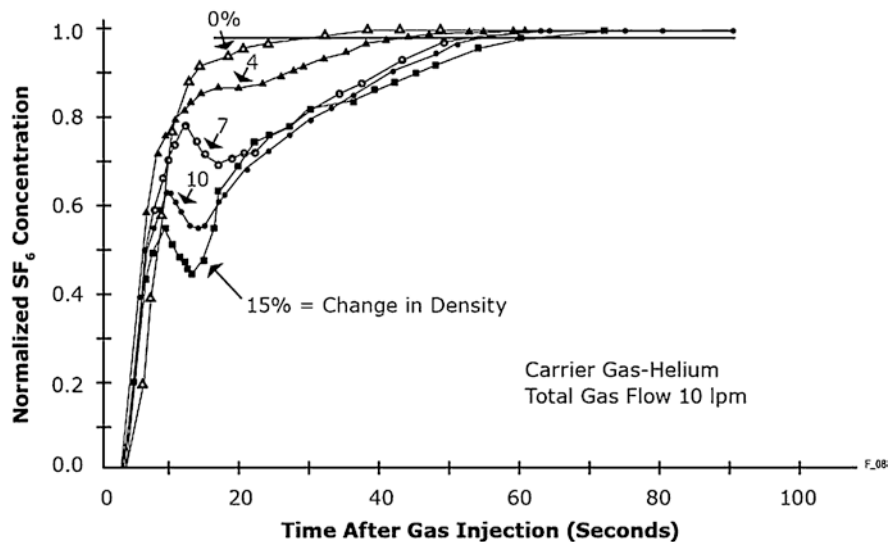
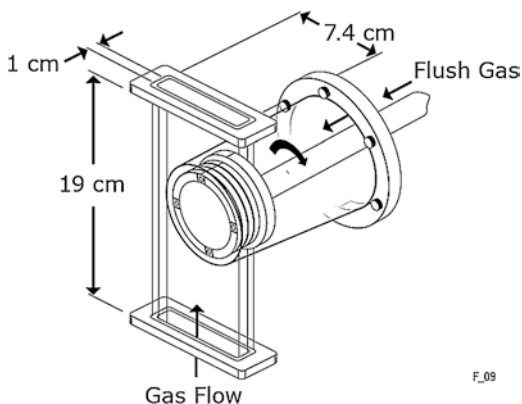


Fig. 2.8 Normalized SF_6 concentration versus time after gas injection. The total flow through the reactor is 10 L/min of helium. Increasing amounts of nitrogen are switched into the gas stream to study the effect of increasing density changes [9]

Fig. 2.9 Schematic drawing of the sidarm chimney reactor [10]



The “chimney” reactor design is shown in Fig. 2.9 was designed and developed in collaboration with Steve Groves and James Caunt. This reactor was optimized for the growth of InGaAsP related materials. By decreasing the cross-sectional area and increasing the gas velocity through the tube, the formation of convective cells is restricted. For the case of InP/InGaAs growth, a large density change can occur when the arsine and phosphine are switched because AsH_3 is about twice as dense as PH_3 . The most obvious way to eliminate convection due to density changes is to density balance the gases switched between the reactor and vent line.

InGaAs strained-layer quantum well (QW) diode lasers with GaInAsP/GaAs alloys operating at 980 nm were successfully produced in the “chimney” reactor.

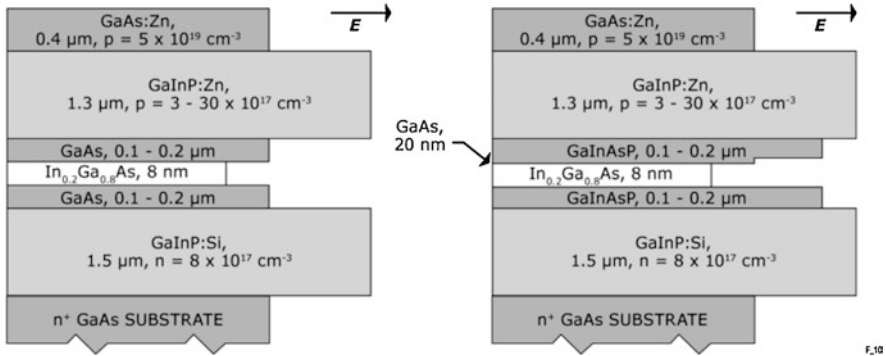


Fig. 2.10 Single quantum well separate confinement heterostructure device designs: on the left, GaAs optical waveguide material, and, on the right, GaInAsP (Energy gap = 1.7 eV) optical waveguide material. Profiles on the right edge show bandgap variation. Layer widths are not to scale [11]

Two types of separate confinement heterostructure QW devices were produced, differing in the optical-waveguide-layer material.

These structures were successfully mass transported and buried heterostructure devices were made. Ridge wave guide lasers with single spatial mode behavior to greater than 50 mW per facet output have also been fabricated from the structures with GaInAsP. These results demonstrated the ability of the “chimney” reactor to produce the state-of-the-art uniform and abrupt GaInAsP materials and laser diodes to near parity with those of AlGaAs alloys (Figs. 2.10 and 2.11).

Accomplishments and Insights

Produced for the first time abrupt interfaces in arsenides and phosphides grown by OMCVD. Modeled and designed a production OMCVD reactor. Produced first GaInP buried heterostructure lasers.

While working at MIT Lincoln Labs made me the engineer I am today, it did not afford me opportunities to develop or hone my social skills, something I identified as a critical gap as my engineering journey and leadership responsibilities progressed.

2.3.3 Gas Source Molecular Beam Epitaxy

Gas source MBE materials were developed at MIT Lincoln Laboratories in the 1990s with my colleague Dr. Paul A. Maki. The narrowest intrinsic photoluminescence linewidths 0.7 meV were obtained by solid source MBE-grown single quantum well structures. These linewidths were obtained by the elimination of impurities and controlling the stoichiometry at the quantum well interface. These impurities were significantly reduced by thermal conversion of the substrate in combination with controlling the V:III flux ratio when growing the quantum well. REF.

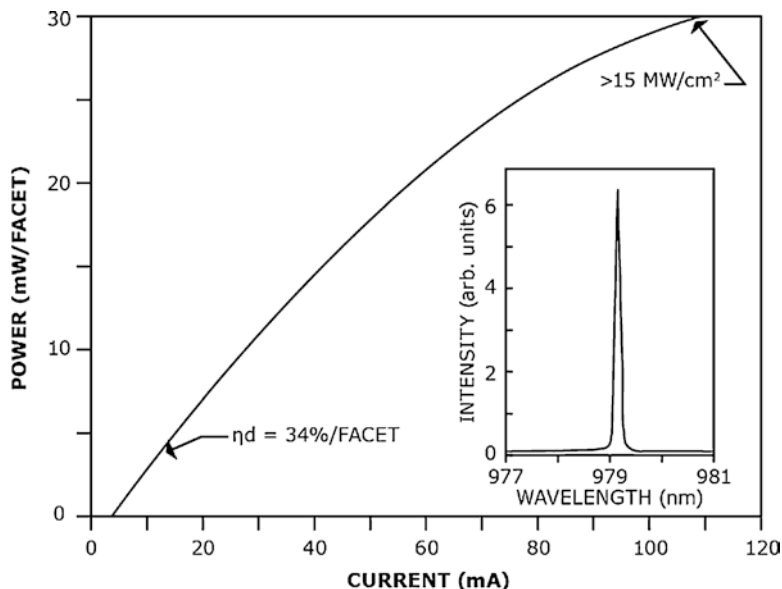


Fig. 2.11 Power per facet versus current in pulsed operation for buried heterostructure device, 1–2 μm wide and 350 μm long, with GaAs optical waveguide layers. The inset shows the emission spectrum at 10 mA with a single longitudinal mode near 980-nm [11]

Studies of growth kinetics between solid source MBE, OMCVD, and GSMBE shed insight into the crystal growth kinetics. The highest purity material was grown by solid source MBE, while the most abrupt interfaces were produced by GSMBE (Fig. 2.12).

An in-depth understanding of interface growth for solid source MBE, gas source MBE, and OMCVD was developed during this time given access to three epitaxial reactors. We were able to explore the material systems referenced below in Fig. 2.13.

Accomplishments and Insights

Characterized III–V material by three different growth techniques: MBE, OMCVD, and GSMBE. We developed an in-depth understanding of the bulk and interface growth and thermodynamics for III–V materials.

2.4 193-nm Lithography—Control and Quantification of Line-Edge Roughness in Resist Patterns

MIT Lincoln Laboratories had a center of excellence for 248, 193, and 157-nm lithography in the 1990s. SEMATECH funded a consortium that supported advanced development and characterization of lithography and dry etch development. A positive tone silylation process was extensively characterized with regards to exposure and defocus

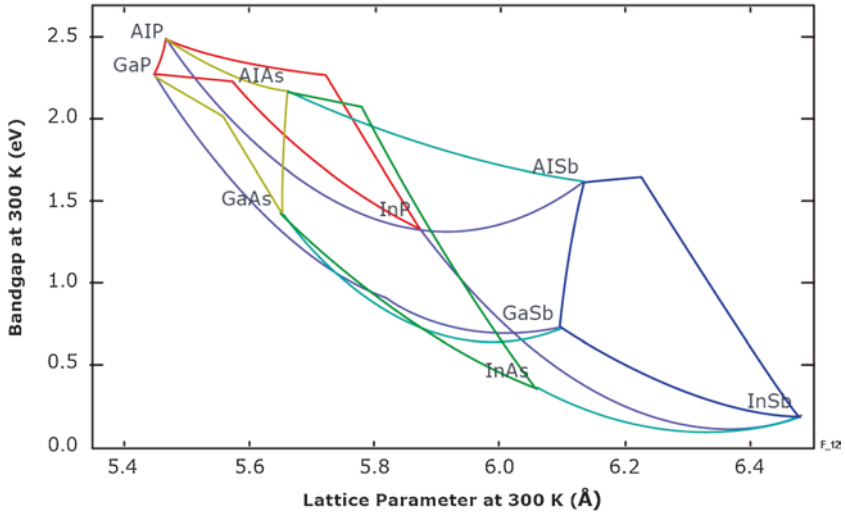


Fig. 2.12 Band gap versus lattice spacing at 300K for III-V semiconductors [12]

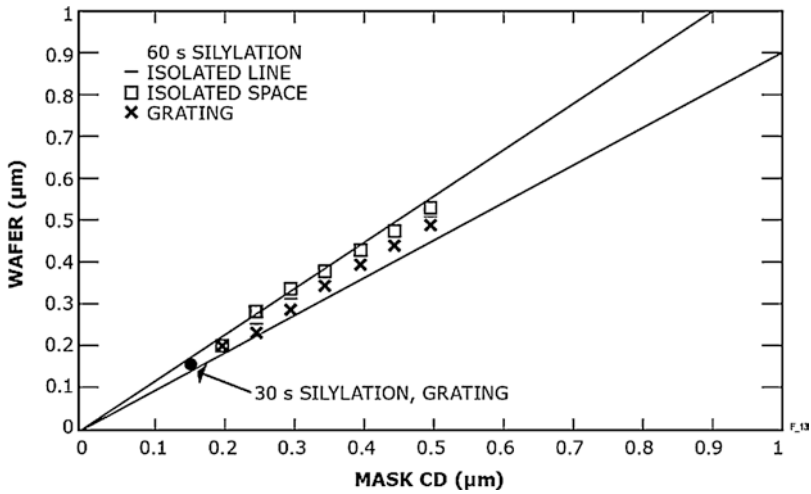


Fig. 2.13 Silylation process linearity at best dose (100 dose units -400 mJ/cm^2). Resist O.76-j. tm -thick PVP silylated with DMSDMA at 90°C and 25 Ton for 60 s was etched under optimized conditions with a 100% over etch. The grating linearity is extended to $0.175 \text{ }\mu\text{m}$ for a 30 s silylation time and 25% over etch. The two solid lines are the acceptable performance, i.e., deviations from the nominal feature size [13]