Inventor, Innovator, Entrepreneur
and
Corporate President
---- Industrialization of the FeRAM ----

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Dedicated To

Ira Duncan McMillan

And

Lilly Bell (Reed) McMillan

Synopsis

The world economy is becoming increasingly global and more knowledge-based [27], [56]. Getting new ideas (not just new technology) into the world market-place quickly and efficiently has become a significant concern for nearly every business on the planet. While the legal, political, language and cultural differences around the world tend to inhibit the rapid distribution of knowledge, the internet (with its satellite network) is now providing a vehicle for nearly instantaneous communication between all members of all societies. With continuous improvement in shipping and transportation technologies, even the distribution of goods and services is beginning to take on new meaning. (Note, for instance, that global positioning (GPS) technology, RFID tags and biometric identification systems are all having a significant affect on air, sea and ground transportation services [63].) As supply and demand adjusts to changing global markets, business practices and organizational structures obviously must change accordingly in order to stay effective and globally competitive. With this in mind, it appears that even the meaning of such words as inventor, innovator, entrepreneur and president should now be re-examined, and perhaps re-defined to accommodate 21st century business and economic conditions. Part of this thesis provides insight into some of these terms and proposes some new models for business operations and, perhaps, business survival, in the 21st century.

A few inventions, with their subsequent technological advancements, move society either forward or backward in every century, depending on the applications of such technology. (It would be hard, of course, to argue that society moves forward, rather than backward, with the invention of weapons and/or instruments of mass destruction.) For instance, the invention of the automobile, the airplane, the transistor and the integrated circuit, all had profound, and generally positive, effects on 20th century society. In this thesis we will investigate the origin and evolution of another technology, the non-volatile ferroelectric memory, that is quite certain to have a significant, and positive, effect on the new ubiquitous society of the 21st century.[1]

Background

Much of this thesis is based on the business and technology experiences of the author, Larry McMillan. McMillan is an entrepreneur from the United States. At the time of this writing (2005) he has forty years experience encompassing the disciplines of inventor, innovator, entrepreneur and corporate executive, *hence the title of this thesis*.[2] In this thesis McMillan's invention of the integrated, non-volatile, ferroelectric memory and his persistent efforts to bring it, along with a number of his other

[1] In the 20th century, most actively addressed (read/write) computer memories (such as DRAM's) required a source of power to maintain data storage. Without a power supply such memories are volatile and cannot store data for long periods for time. Non-volatile memories do not require a power supply to store data.

[2] McMillan began working as an engineer and manager in the semiconductor industry in 1965, before either Bipolar or MOS integrated circuits had entered production (at Motorola). He has worked in nearly every segment of the integrated circuit industry, ranging from Research and Development to Production Engineering to Corporate Management to Consulting for a number of international corporations. Note the brief listing of his U. S. corporate experience (in Appendix D), the listing of his publications and presentations (in Appendix C) and the listing of his patents (in Appendix B).

inventions, to commercialization, should provide some insight into the actual meaning of many of the terms associated with entrepreneurial engineering.[3]

Purpose of research

The research of this thesis defines and elucidates some of the practical and theoretical aspects of entrepreneurial engineering. Concurrently, research into the origins of ferroelectricity and the ferroelectric random access memory (FeRAM) will provide support for the idea that most inventions actually originate from existing knowledge that has accumulated over hundreds of years. All of this should also help disperse some common misconceptions concerning the origin, authenticity, ownership and status of this technology as well as its importance for 21st century ubiquitous society. We will also try to achieve some understanding of the globalization that had to occur for ferroelectric memories to play into an industry as complex as the semiconductor industry. Throughout this thesis, this experience will be registered against the academic foundation achieved at Kochi University of Technology.

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[3] McMillan received B.S and M.S. degrees in Physics, Math and Electrical Engineering in the U.S. but most of the academic background reflected in this thesis was achieved through graduate studies in Entrepreneurial Engineering (with Professor Gota Kano), Business Theory (with Professor Keizo Baba) and Technology Management (with Professor Osamu Tomisawa) at Kochi University of Technology. (Reference the thesis bibliography.)

Significance of research

The significance of this research becomes evident with an understanding of the historical significance and economic potential of ferroelectric memory technology. (Of course, the real significance of this entrepreneurial engineering exercise must ultimately be measured by the resulting benefits to society.) The author's invention of the integrated ferroelectric random access memory and his continuous efforts to bring this technology to commercialization has resulted in much of the revolutionary product and knowledge base now driving the nonvolatile technology growth predicted by S. M. Sze in his book *ULSI Devices*, (published in 2000, reference [19]). This thesis will show that the author was not only a primary inventor of this technology but also that, over a period of three decades, he played a crucial and leading role in its development and commercialization (reference Figure 1.1 in Chapter one).

With reference to economic potential of the technology, we note that millions of ferroelectric memory (FeRAM) integrated circuits are now being manufactured and sold, especially in Japan and other parts of Asia. Microcontrollers, RFID chips and many other integrated systems are now being embedded with ferroelectric random access memories (FeRAM’s), and the US government is now incorporating radiation-hardened ferroelectric memory devices into their satellite and space probe systems.

Summary of contents

Following a brief introduction in Chapter 1, we define some of the differences between the inventor, the innovator and the entrepreneur in Chapter 2. We also discuss the evolution from inventor to entrepreneur and explore the environment that cultivates their respective activities.

In Chapter 3, we address the evolution and history of ferroelectric technology from its earliest roots to the invention (by the author) of the integrated ferroelectric memory and ultimately to the introduction of viable non-volatile memory products to the world market place. This process occurred over many years and several generations of scientists and engineers. This chapter also introduces Symetrix Corporation, a company co-founded and co-owned by McMillan and shows the strategic foundation upon which its core competency was developed.

Chapter 4 addresses some of the management styles, cultural differences and corporate structures that will mold global business relationships in the 21st Century. Chapter 5 outlines some ideas on sustainability and business growth and Chapter 6 discusses protection of intellectual property and cost minimization through global business relationships.

Chapter 7 explores the evolution of the new corporation in a changing business and philosophical environment. Conclusions are presented in Chapter 8.

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Chapter 1

Introduction

1.1 The Status of Non-Volatile Memory

Since the invention of the computer, non-volatile (or pseudo-non-volatile) memories such as ROM's, EEPROM's, FLASH, etc., have been used to store data and program code. However, with the exception of ferrite core memories of the early sixties, most of these semiconductor non-volatile memories wear out after less than one million erase/write commands, consume considerable power, and write at microsecond or millisecond speeds. Ferroelectric non-volatile memories (FeRAM's), however, have tenth of nanosecond, symmetric, read/write speeds (at the molecular level) and show very little degradation even after more than 100 billion erase/write operations.

FeRAM's are currently being used in stand-alone memories, smart cards, RFID tags and in many other consumer products. Commercially, more than 100 million FeRAMs have been introduced to the market and now, due to continuous upgrades, they are becoming key candidates for system-on-chip applications.

S. M. Sze predicted in his book *ULSI Devices*, (published in 2000) that non-volatile memory would become a significant technology driver exceeding the market size of transistors, DRAM's and CPU's by about 2010 [19]. Sze placed the accelerating part of his proposed growth curve for non-volatile memories, very accurately, twenty years after the market introduction of DRAM's and CPU's. It seems unlikely that Sze was aware of the progress being made with ferroelectric devices, or that he was referring to ferroelectrics in any way, when he published his growth curve for nonvolatile memory.[7] It, therefore, becomes quite interesting to note that his growth versus time curve (Figure 1-1) coincides exactly with the S-curve associated with the invention, development and industrialization of the FeRAM. Figure 1-1 shows the superposition of the two curves with McMillan's colored S-curve representing FeRAM's.

[7] There are several other "non-volatile" technologies, such as MRAM, Ovonic, etc., that are presently in research; however, FeRAM technology is already mature, in production and exhibits real certainty for future applications..

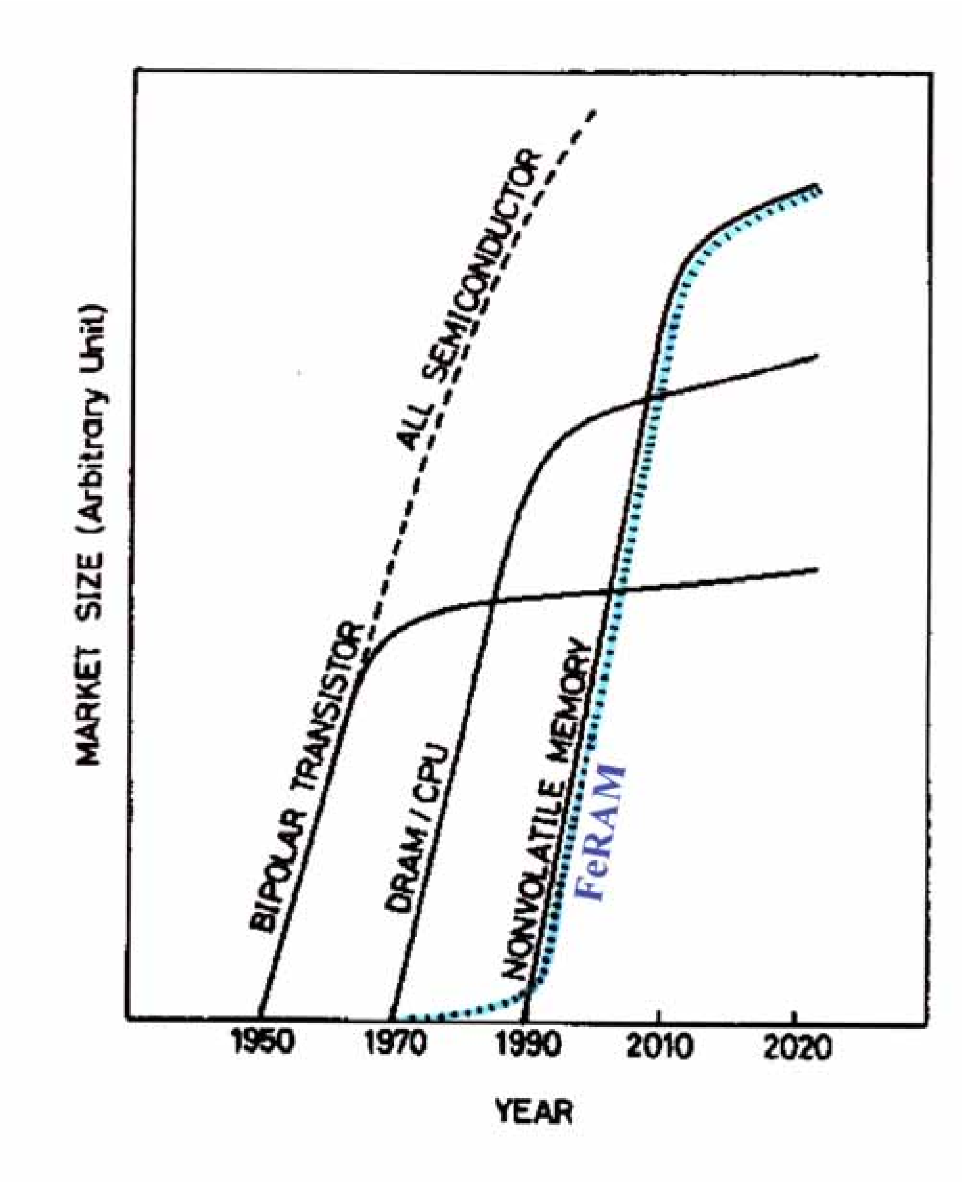

Figure 1-1. Sze's Growth curves for different technology drivers. The superimposed colored line represents McMillan's S-curve for FeRAM's. (After Sze, *ULSI Devices*, pg. 13, [19])

1.2 Innovation Generators

According to Christensen, the semiconductor industry is based on a disruptive technology, namely the transistor, which displaced the vacuum tube in the 1950's [25]. Looking back over the last century it becomes apparent that the invention of the transistor was not only disruptive but also one of several related inventions that may now be called *innovation generators.*[8] The invention of the transistor by Shockley, Brattain and Bardeen at Bell Labs in 1947, inspired Jack Kilby to invent the integrated circuit in 1958.[9, 10] The integrated circuit would never have been invented without the prior invention of the transistor. In 1968 George Rohrer used water soluble KNO_3 to build a capacitor like thin film ferroelectric memory on a glass slide. Indirectly, this was related to the transistor and the integrated circuit. Rohrer, however, was not particularly interested in the processing of transistors and integrated circuits, but was inspired by the work of Schubring, Anderson,Von Hippel and several others who were trying to find a replacement for magnetic core memories. It is interesting to note that the transistor, the integrated circuit and the ferroelectric memory all originated from extremely simple appearing, and yet very technologically complicated, initial prototypes (Figure 1-2).

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[8] "Innovation Generator" is a term devised by the author to describe inventions and/or innovations that cause many people to generate more inventions and innovations.

[9] It should be noted that Julius Edgar Lilienfeld proposed the basic principle behind the MOS field-effect transistor in 1925. Reference Lilienfeld U.S patents 1,745,175 (1930) and 1,900,018 (1933) [67]

[10] Nobel laureate Jack Kilby, died of cancer at age 81, June 22, 2005.

The invention of the integrated ferroelectric memory by McMillan in 1975 was inspired by the previous invention of the transistor, the bipolar integrated circuit, the MOS integrated circuit, Rohrer's ferroelectric memory and many others. (A brief history of ferroelectric memories will be given in Chapter 3.) As with the transistor and the integrated circuit, the integrated ferroelectric memory has also become an "innovation generator" (Figure 1-3) causing the formation of thousands of new companies and the production of millions of new products as well as inspiring new research and development interest in almost every country on the planet.

1.3 Ferroelectric Memories

From simple beginnings, ferroelectric memories have now progressed to the point where they are not only competing with other integrated circuits, they now display some characteristics that other IC's cannot match. With their low power consumption, radiation hardness, fast read-write cycle times and nearly infinite endurance, ferroelectric non-volatile memories (FeRAM's) are now widely recognized as superior to other commercially available nonvolatile devices such as electrically erasable programmable read-only memories EEPROM's and FLASH (Figure 1-4). It is also apparent that FeRAM's may soon be replacing many devices in existing products and appearing in a broad spectrum of new, and/or not yet designed, products that will have a significant effect on 21st Century society (Figure 1-5).

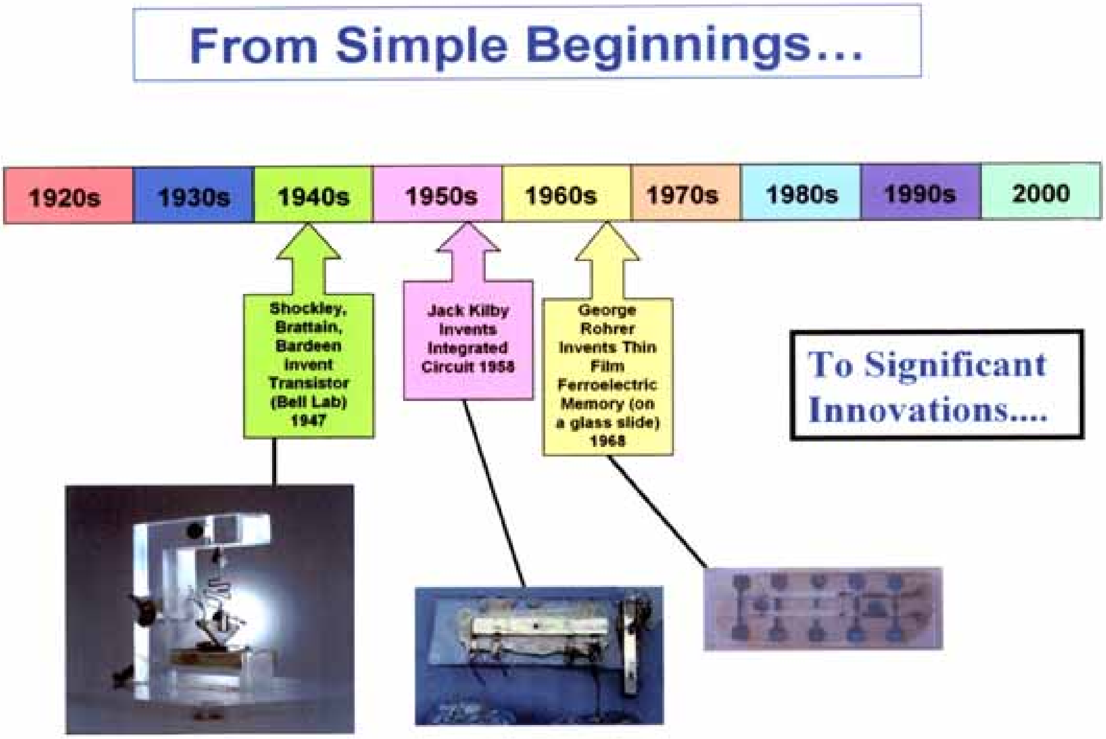

Figure 1-2. Some significant invention/innovations of the 20^{th} Century [53] (Note the apparent simplicity of the prototypes.)

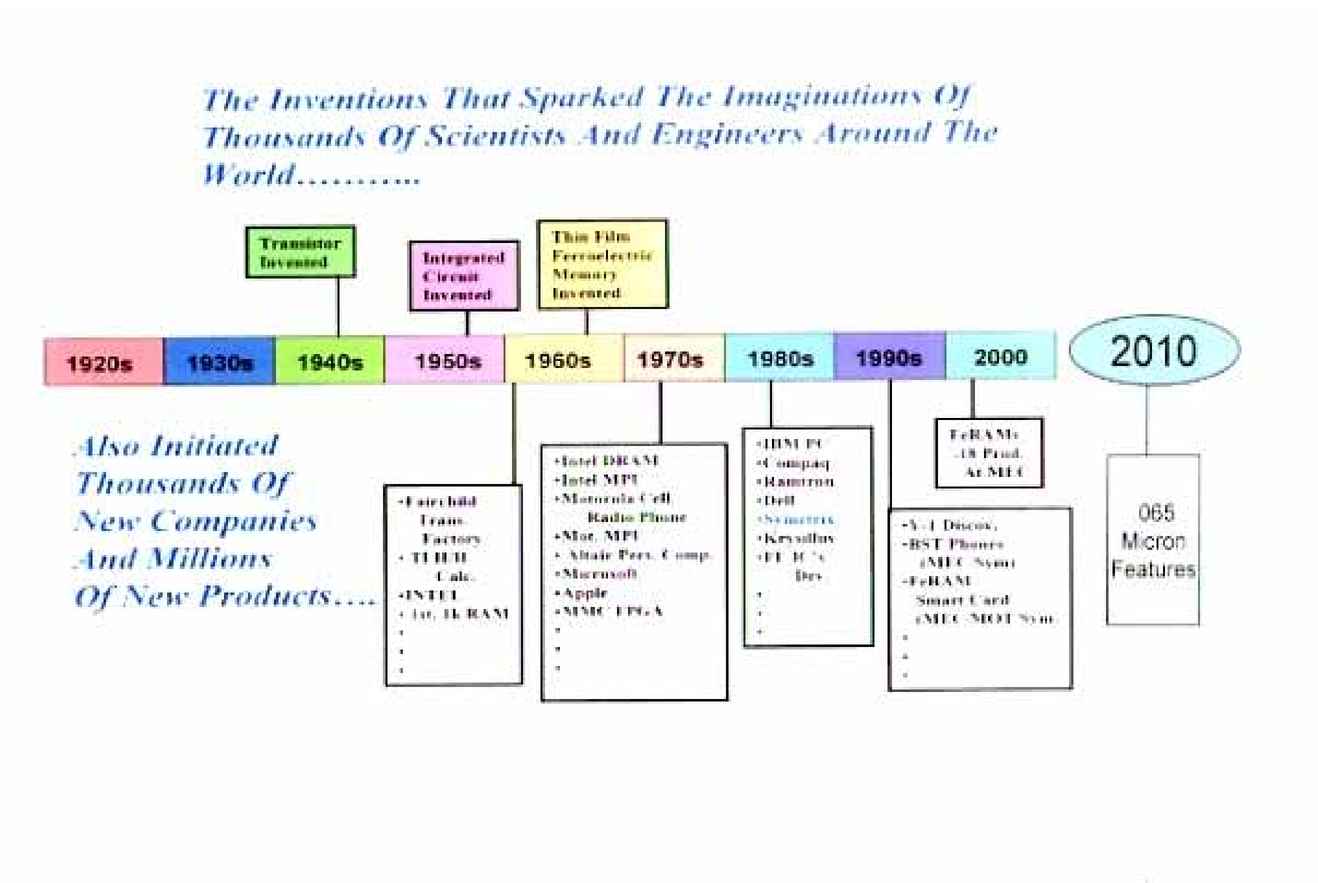

Figure 1-3.   Innovation generators of the 20th Century

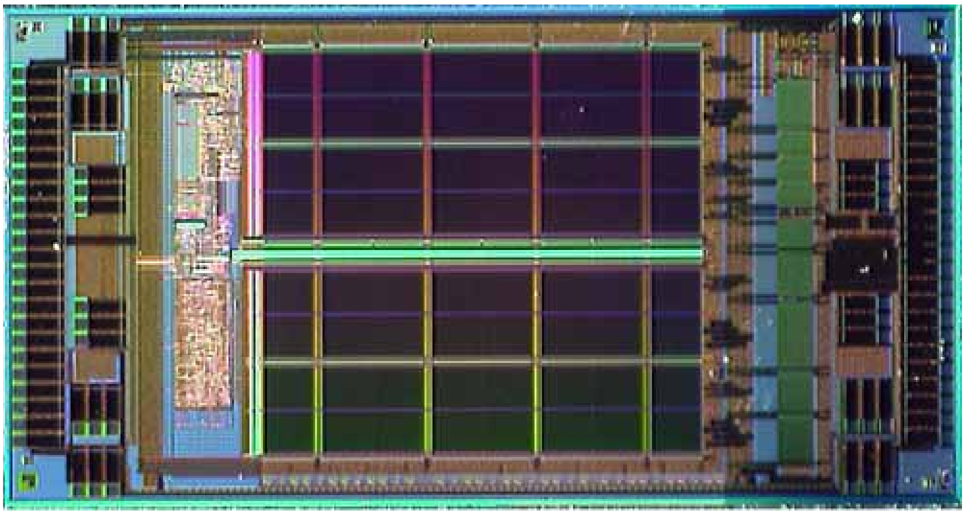

Figure 1-4. FeRAM integrated circuit. (Photo courtesy of Panasonic Corporation.)

RFID Cards	**Televisions**
Helicopter: control, navigation, communication	**VCRs**
Medicine administering systems	**Automatic doors**
Smart hospital bed with sensors and communication	**Electric wheelchairs**
Patient monitoring system	**Smart briefcase with fingerprint enabled lock**
Surgical displays	**Ambulance medical and communication equipment**
Digital thermometers	**Automatic irrigation systems**
Portable data entry systems	**Jet aircraft: control, navigation, communicaton, autopilot, collision-avoidance, in-flight enterntainment, passenger telephones, etc.**
Pacemakers	**Laptop computer (contains embedded systems)**
Portable stereos	**Automatic lighting**
Satellite receiver systems	**Pump monitoring system**
Credit/debit card readers	**Lottery ticket dispenser**
Barcode scanners	**Traffic light controllers**
Cash registers	**Police vehicle (data lookup, communication, sirens, radar detector, etc.)**
ATM machines	**Handheld communicator (walkie-talkie)**
Automobile (engine control, cruise control, temperature control, music system, anti-lock brakes, active suspension, navigaton, toll transponder, etc.)	**Fire-control onboard computer**
Cordless phones	**Microwave oven**
Coffee makers	**Smart refrigerator**
Rice cookers	**In-home computer network switch**
Portable radios	**TV-based Web access box**
Programmable ranges	**House temperature control**
Portable MP3 player	**Home alarm system**
Digital camera	**Point-of-sale system**
Electronic books	**Video game console**
Hearing aids	**TV remote control**
Dishwashers	**Electronic keyboards/synthesizer**
Electronic clock	**Fax machine**
Streaming video cameras	**Scanners**
Electronic wristwatches	**Wireless networking**
Pagers	**Telephone modem**
Cell phone	**Cable modems**
CD players	**Printers**
DVD players	**Portable video games**
Smart speakers	**Personal digital assistant**
Stereo receivers	**Portable digital picture viewer**
TV set-top boxes	

Figure 1-5. A few applications for FeRAM's

To the general public, all of this may appear to have happened very recently (Figure 1-1). That, of course, is not the case. This "new" ferroelectric random access memory (FeRAM) technology is really the result of a difficult journey that started many years ago encompassing the resources and lives of hundreds of people. The author, alone, has dedicated over 35 years of his life to bring this technology to commercial reality (Figure 1-6).

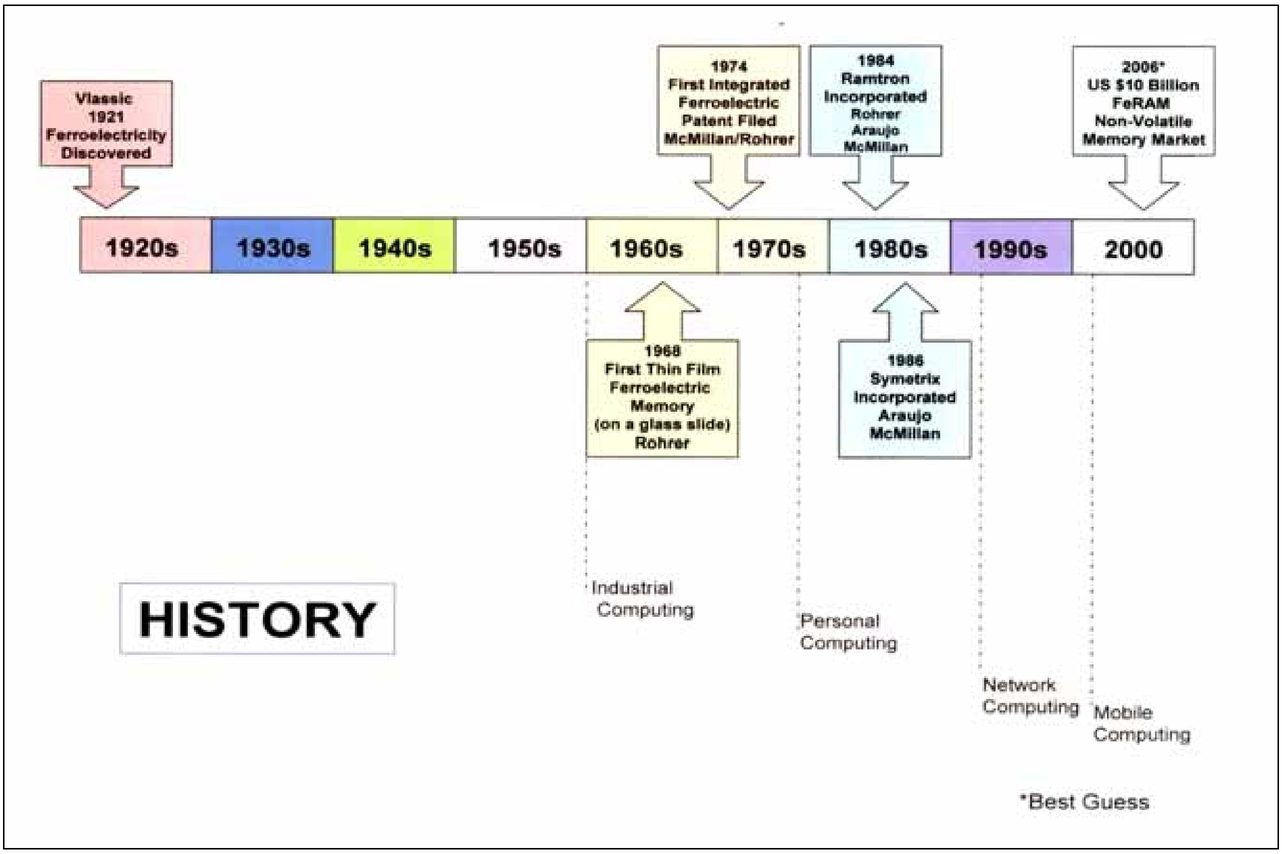

Figure 1-6. A brief history.

Throughout the author's career, especially during the years of his involvement in ferroelectric technology, he experienced the roles of inventor, innovator, entrepreneur, etc., without really being cognizant of what those terms meant. In like manner, he was unaware that some of his efforts might possibly result in breakthroughs that would have significant and positive effects on global society. In many respects, this thesis represents part of the author's awakening to those possibilities and his struggle to achieve that understanding.

Chapter 2

From inventor to entrepreneur: definitions and evolving characteristics

2.1 Invention

No one really knows exactly when, why, or how our ancestors achieved the ability to visualize ideas in their minds and then bring those ideas into existance. From the fossil record it appears that sometime between 50,000 and 100,000 years ago primative man evolved millions of new brain cells that, somehow, established the ability to create images and then express those images through the generation (invention) of new tools and various aesthetically pleasing artifacts. [11]

It appears that mankind alone has this imaginative capability. It could be argued that this ability to create and/or invent is the single most significant factor differentiating modern human beings from all other organisms found on earth. It could, likewise, be argued that every person, by the very fact that they are human, has the potential to discover, express ideas and build objects that were previously non-existant.

[11] The word "invention" comes from the Latin verb meaning "to come upon" [10].

Having the potential to invent and actually being inclined to exercise that ability, however, are very disparate concepts. Innumerable psychological, financial, environmental and socialogical factors effect the thought processes of potential inventors such that relatively few (compared to the total world population) ever attempt to invent anything. Everyone interprets the world around them differently than everyone else. The same insights that drive some people to despair can drive other people to think of solutions, new products or new methodologies. No one knows, of course, but the inventor of glass manufacturing may have been someone who observed glassy materials in the embers of a beach fire sometime in the far distant past. Perhaps George de Mestral became upset by cocklebur seeds sticking to his jacket, which inspired him to invent Velcro. Frustration with the many errors found in mathematical tables may have led the mathematician Charles Babbage to think of the invention of the computer. No one, of course, will ever know what really happened in the inventor's, or anyone else's, mind at any point in time.

Much has been written about the inspirational origin of various inventions. Common thought channels range from simple frustration, to analysis of data, to serendipitous encounters (Figure 3-28) [21].[12] It may not be intuitively obvious, but to the author at least, it appears that most inventions actually originate from knowledge of something that already exists. It could be calculus, bicycles or railroads, but every invention appears to draw, in some way, on the accumulation of know-how that has built up over thousands of years. To support this idea, the origins of

[12] Serendipitous – finding something valuable or unexpected by accident or chance.

technological know-how predicating the discovery of ferroelectricity and subsequently the invention of the FeRAM are detailed later in this thesis.

With the rapid accumulation of know-how and the world population increasing at a phenomenal rate, one could easily assume that the invention generation rate should be increasing accordingly.[13] Indeed, this may be true in some parts of the world, but certainly not in those areas that are economically or politically stressed. We have no way to measure the number of inventions that are not documented or never reach the patent stage. We can note, however, that the large majority of issued patents fall generally in those regions of the world that incourage freedom of expression and have well developed economies (Figure 2-1). This would seem to support the idea that the propensity to invent is a strong function of the inventor's political and economic environment.

For most of recorded history it appears that no one really believed that anyone should receive special consideration for their creations. Until the late 1400's it appears that inventions were, somehow, considered community property.[14] (Remnants of this mentality are still present in those parts of the world still adhering to communist doctrine.) Even with the thousands of international treaties, laws and regulations presently in force to protect inventors and their intellectual property, there is still little protection for the

[13] It took until 1950 for the world population to reach 2.5 billion. Since then, it has More than doubled, reaching 6.1 billion in 2000. In the 50 years between 1950 and 2000, the world grew in population by an amount equal to all previous growth in all of human history. [55]

individual inventor from practitoners of unscrupulous legal and business activities.

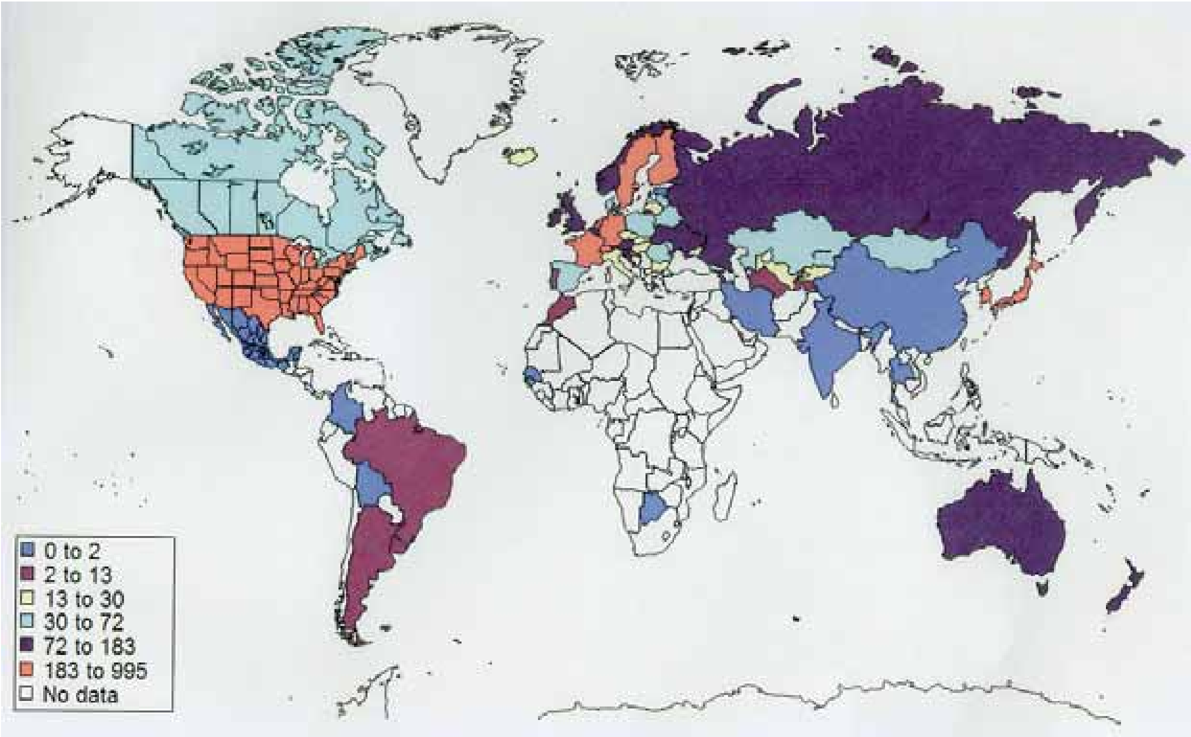

Figure 2-1. Patents per million population

(After Carnel, Ref. [3])

For instance, according to James White, (page 2, reference [5]):

> "It is estimated that every year 25 to 30,000 would-be inventors in the U.S. alone are talked out of $500 to $25,000 by people

[14] The first systematic attempt to protect inventors by a form of patent granting exclusive rights to an individual occurred in Venice, Italy in 1474.

with no interest whatsoever in the inventor's invention, only
their money."

White also estimates that this probably amounts to around $300 million per year and that inventor support, such as patent attorneys, patent agents, prototype makers, machine shops, manufacturers, etc., (in the United States, alone) collect about $1.5 *billion* per year [5]. Is it any wonder that most inventors become extremely protective of their intellectual property?

At a fundamental level, discriptions of inventor characteristics are probably as complicated as the discriptions of divergent world cultures. It may be easy to simply follow Webster's dictionary and define an inventor as "someone who creates or produces something for the first time" and an invention as "a creation of the imagination", but these definitions really do little to illuminate the complicated mental and socialogical mechanisms that ultimately lead to most of the worlds *known* inventions.[15] We can, however, gain some insight into these mechanisms by adding the concept of innovation to the basic definitions of inventor and invention.

[15] Webster's New Dictionary of the English Language, Merriam-Webster, Incorporated, Popular Publishing, New York, 2003.

2.2 Innovation

The concept of innovation probably entered the language of sociology through Gabrial Tarde (1843-1904) according to Fontan [22]. Tarde proposed that the accumulation of inventions – "innovations" – makes societies evolve and gradually alter human behavior [22]. Tarde apparently did not persue this concept and it was not until Joseph Schumpeter (1883 – 1950) that a better definition of innovation emerged. Schumpeter believed that innovation lies in the *process* that leads to social change through use of inventions [22], [23]. From this we can see that the terms "innovation" and "invention" might be interchanged and easily confused. It appears that innovation could be defined as "the *process* that transforms new ideas or concepts into commercial value," or "the turning of a new concept into widespread use".[16] In a broad sense, we might say that an invention is the product of a person's mind and that it (the invention) is capable of self existence. In that sense, an inventor is really the *creator* of intellectual property and an invention perhaps becomes an innovation only when it is enhanced with existing knowledge and enters the *commercial* mainstream. If future developments are influenced by this combination the author maintains that the innovation becomes an *innovation generator*. (See the definition of *innovation generator* in footnote 5.) With these concepts, the innovator is actually a *change maker* and innovation becomes an economic and social, rather than a technological term (note the quote from Peter Drucker in Section 2.4.).

[16] Webster's New World College Dictionary defines innovation as "..something newly introduced…change in the way of doing things…."

2.3 McMillan's Stagnation Wall

Figure 2-2 separates some characteristics of inventors and innovators and illustrates the transition from invention to innovation. This illustration also proposes that a primary stagnation wall often differentiates or separates the inventor from the innovator.[17] This stagnation wall is generally brought about by inventor protectionism and subjective distractions from value building. Often this wall appears because inventors tend to inflate the value of their inventions (as perceived by potential investors) or because they fear losing their intellectual property to unscrupulous financial and/or business practioners. An example of the latter, experienced by the author, is presented later in section 3.6.

Inventors, in general, cannot become innovators unless they overcome the stagnation wall.[18] By most simple definitions, we imply that inventors are creators (producing something with their *individual* minds that never before existed) and that innovators effect economic change by somehow implementing what the inventor has already brought into existence. It is often this sense of *individual* creation, and the *personal* need to protect that creation, that drives the inventor's thinking as they face the stagnation wall. This sense of protectionism may be similar to the feeling that a parent has for their children. In like manner, inventors often cannot put a monetary

[17] The term, "stagnation wall" was invented by the author.

[18] No one knows for sure; however, it appears that no more than 2 to 7% of the patents issued ever return a profit to the inventor [69].

value on their inventions any more than parents can put a particular value on their children.

As evidenced by the low percentage of inventions that reach maturity or provide profit, most inventors have considerable difficulty overcoming the stagnation wall. In some respects it seems that the primary mediator of the inventor's protectionism may simply be the allure of wealth and recognition provided by innovation.[19] This, however, is an obvious over-simplification that may apply to some, but not all, inventors. The author considers himself far outside the group driven by wealth and recognition.

In the following chapters, the author provides a few examples of patent-sharing, joint development and other procedures that may solve many, but not all, problems related to the stagnation wall.[20] It seems more likely that successful inventors must ultimately look beyond their individual greed and ego inclinations to embrace the enhancement of society if they are to really overcome their individual stagnations walls.

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[19] "But in science the credit goes to the man who convinces the world, not to the man to whom the idea was born," Francis Darwin, [17].

[20] It should be noted that most of the author's patents are *shared* with other individuals. This practice of adding "several inventor's" names to patents, evolved from political, financial and bureaucratic considerations and may confuse or violate the fundamental concept of *individual* creativity. It does, however, provide a simple route over the stagnation wall problem.

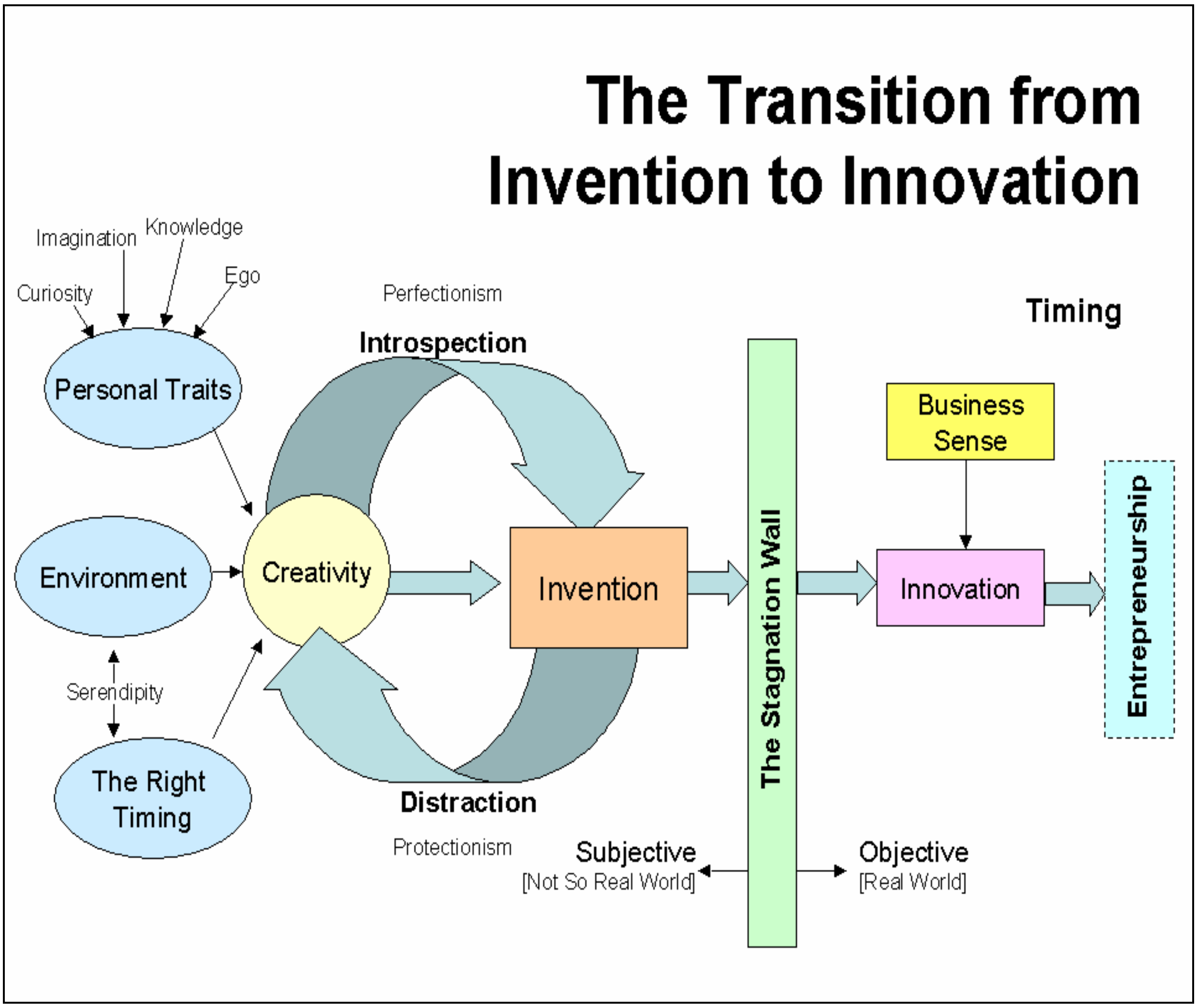

Figure 2-2. The transition from invention to Innovation: an illustration of McMillan's "Stagnation Wall"

2.4 Entrepreneur

If the innovator is the creator of change, then the entrepreneur must be the *risk taker and merchant of change*. The word entrepreneur originates from the French word, entreprendre, which means "to undertake." The Merriam-Webster Dictionary defines the entrepreneur as one who organizes, manages, and assumes the risks of a business or enterprise. In reality the concept of entrepreneurship has a wide range of meanings. On the one extreme an entrepreneur is a person of very high aptitude who pioneers change, possessing characteristics found in only a very small fraction of the population. On the other extreme of definitions, any one who wants to work for himself or herself could be considered an entrepreneur.[21]

Schumpeter maintained that entrepreneurs sometimes put themselves at risk while introducing new products, production innovations and new organizations [23]. In almost all definitions of entrepreneurship (and there are now many), there appears to be agreement that entrepreneurs (1) take initiative, (2) organize social and economic resources to practical account, and (3) accept risks and failures [24].

It is interesting to note what Peter Drucker has said along these lines. The following is a direct quote from, Drucker, *Managing in the Next Society*, page 95, reference [56]:

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[21] People with vision usually have some control over their own lives. People with no vision are generally controlled by others (unknown source).

> *"In this country (USA) we, by and large, still believe that entrepreneurship is having a great idea and that innovation is largely R&D, which is technical. Of course, we know that entrepreneurship is a discipline, a fairly rigorous one, and that innovation is an economic not a technical term, and entrepreneurship creates new business...."*

How can anyone beat Drucker in simple prose?

The popular press (various sources) attributes many rather confusing characteristics to entrepreneurs that the author feels compelled to comment on. A few examples follow:

- *They are willing to work long hours, with patience and perseverence.*
  The author's opinion: Not necessarily so. A good entrepreneur usually trys to work his/her way out of a job, therefore minimizing work hours because he/she is tenacious and impatient .

- *They love challenges and show tolerance for ambiguous, unstructured situations.*
  The author's opinion: Somehow this sounds more like the characteristics of an inventor. Most of the entrepreneurs known to the author are somewhat intolerant to ambiguous and unstructured situations.

- *They possess a desire for change and constant improvement.*
  The author's opinion: Agree. Good entrepreneurs should monitor

social trends and try to adopt new technologies to those trends.

- *They listen and communicate well.*
  The author's opinion: Not necessarily so. The author knows some self proclaimed entrepreneurs that seem to listen only to themselves.

- *They are independent, extroverted and often driven by incredible ego.*
  The author's opinion: Sometimes, but not always, true. Sometimes self confidence and determination are manifested as egocentric behavior. It is also possible to be introverted and still act in an extroverted way under certain circumstances.[22]

- *They learn quickly, enjoy feedback, and are able to learn from their mistakes*
  The author's opinion: You don't need to be a scholar to be an entrepreneur.

- *They are self-confident and determined to succeed.*
  The author's opinion: In general this seems to be true.

- *They generally want to make all, or most of, the decisions.*
  The author's opinion: Not always true. Really good entrepreneur's should be team players. Dictator-like decision tactics are not very well received by anybody, especially in the new global society.

[22] The author appears to be extroverted but is actually quite introverted.

- *They love to take calculated risks.*

  The author's opinion: Schumpeter was right. Good entrepreneurs should not be afraid to take risks.

- *They are able to exert influence and inspiration on others without a need to impose status or power.*

  The author's opinion: This appears to be generally true. However, unfortunately, some entrepreneurs will impose status and power to convince or influence others, especially if there is a lot of money involved in the deal. Note closely Figure 2.3 below.

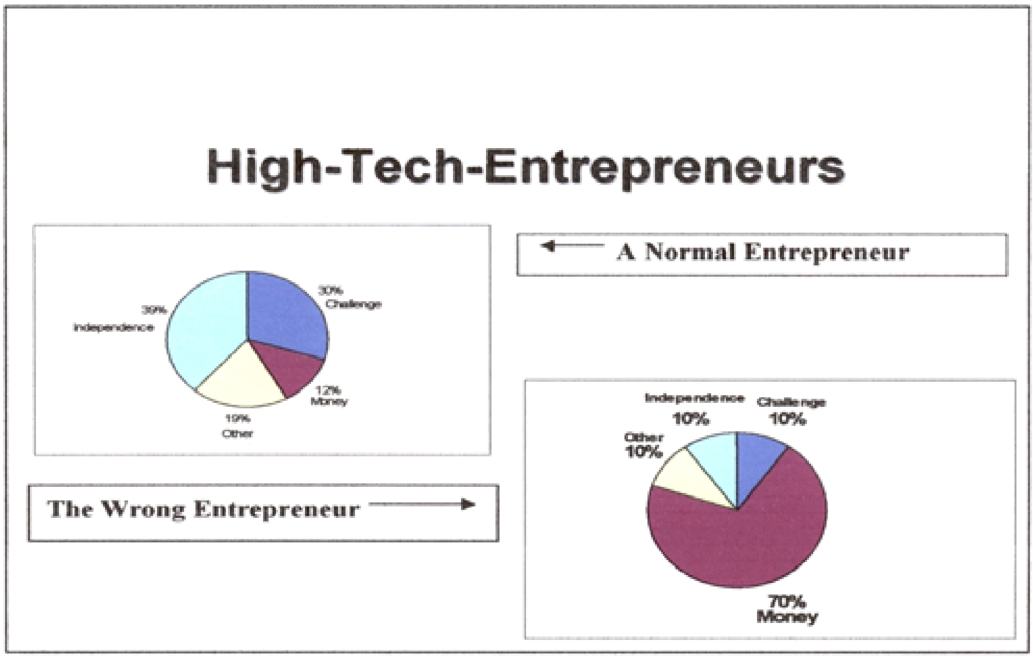

Figure 2-3. “Right” and “Wrong” Entrepreneurs

(After Oxford University Survey, 2003, reference [57].)

It is generally believed that these characteristics, along with know-how, personal contacts, and business expertise, somehow separate successful from unsuccessful entrepreneurs. If this is true then it seems obvious that there must be a minimal set of individuals in the world satisfying the requirements of successful entrepreneurs.

2.5 McMillan's Heirarchy Of Mentality Model

It appears to the author that it is difficult, or impossible, to list a firm set of characteristics that apply to all successful people at all times. The author believes however, that there may be a loosely connected hierarchy of *mentality* separating leaders, managers, entrepreneurs, innovators, and inventors from visionaries and dreamers. In reality, of course we can easily imagine visionaries as dreamers, and dreamers as visionaries, with a subtle difference in the respect given to visionaries. (Note the simple model shown below in Figure 2-4.) Referencing this model, we see that visionaries do not have to be leaders, leaders do not have to be entrepreneurs, entrepreneurs do not have to be managers, innovators do not have to be inventors and inventors do not have to be dreamers. In like manner, dreamers are not necessarily inventors, inventors are not necessarily innovators, innovators are not necessarily managers, managers are not necessarily entrepreneurs, entrepreneurs are not necessarily leaders and leaders are not necessarily visionaries. After saying all of this, it should still be obvious that some individuals might exhibit the characteristics associated with all of these titles at some point in time.

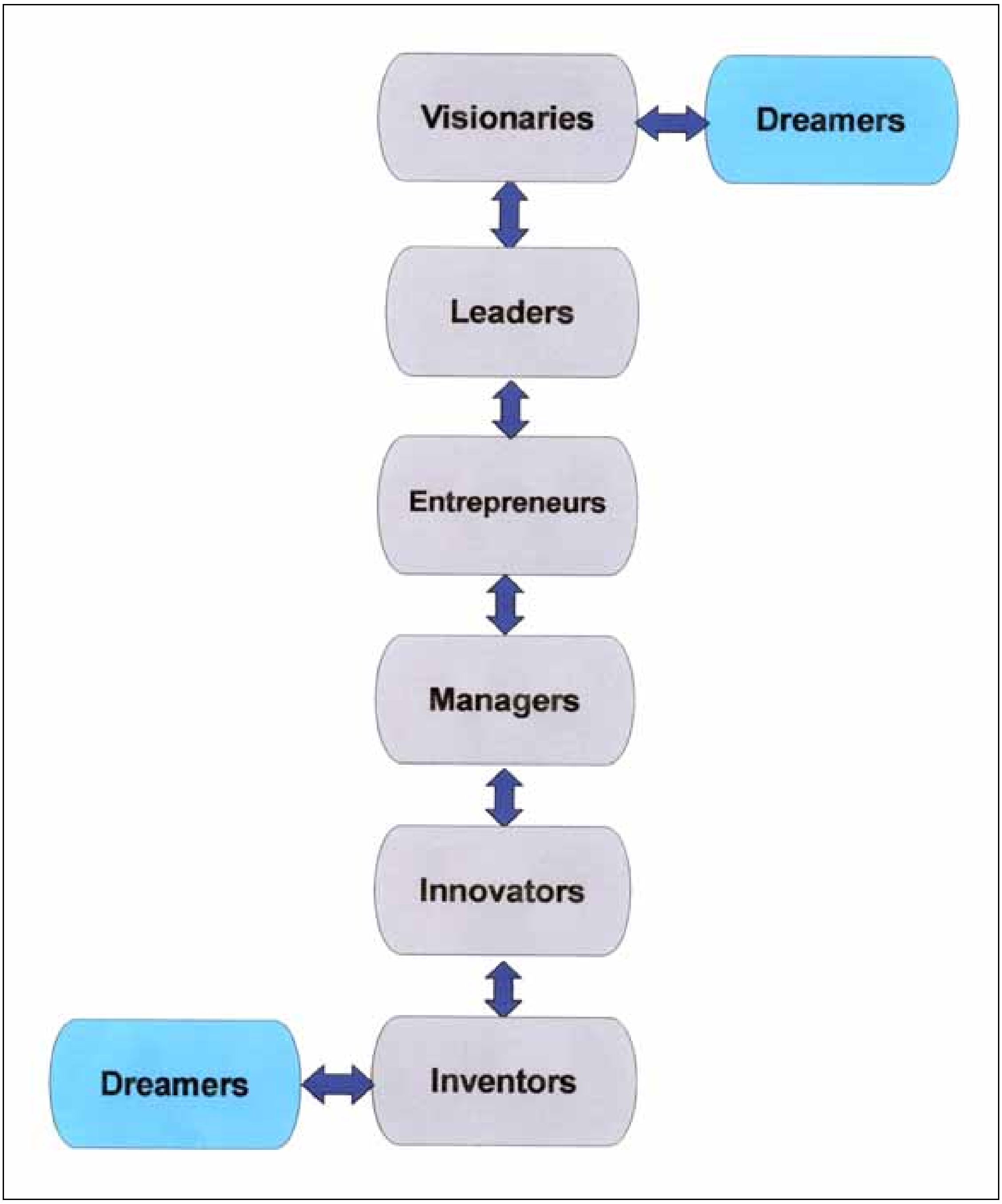

Figure 2-4. McMillan's

Heirarchy Of Mentality Model

Again, directly quoting Drucker, *The Essential Drucker*, page 323, reference [59]:

> *"What we need is an entrepreneurial society in which innovation and entrepreneurship are normal, steady, and continual. Just as management has become the specific organ of all contemporary institutions, and the integrating organ of our society of organizations, so innovation and entrepreneurship have to become an integral life-sustaining activity in our organizations, our economy, our society. This requires of executives in all institutions that they make innovation and entrepreneurship a normal, ongoing, everyday activity, a practice in their own work and in that of their organization."*

Again, Drucker sums it up rather nicely, and the author fully agrees with Drucker.

Chapter 3

Ferroelectric memory:

From invention to industrialization

3.1. The early history

The discovery of ferroelectricity did not occur in a vacuum. It probably resulted from a long history of observation that, under certain conditions, some materials could become "charged", generate sparks and attract small pieces of paper, wood, etc.[23] It appears that this phenomenon was not investigated scientifically, however, until about 1824, when Sir David Brewster, a Scottish scientist, first used the term pyro (fire) electricity to describe materials that change polarization amplitude when heated [65].[24]

In the early 1880's Pierre and Jacques Curie discovered that some naturally occurring crystalline materials, such as quartz, could change shape when subjected to an electric field. This property, which they named piezoelectricity, was later also found in some artificially produced crystals such as ammonium dihydrogen phosphate, lithium sulphate and sodium

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23 Theophrast noted in 314 BC that tourmaline becomes charged when heated [65].

24 It is questionable how Brewster did his measurements. The author could find no reference documents.

potassium tartrate tetrahydrate.[25] One of these materials, sodium potassium tartrate tetrahydrate, ($NaKC_4H_40_6.4H_20$ – also known as Rochelle Salt) appeared to exhibit a higher piezoelectric effect than most other materials, and later became known as the first discovered ferroelectric material.[26]

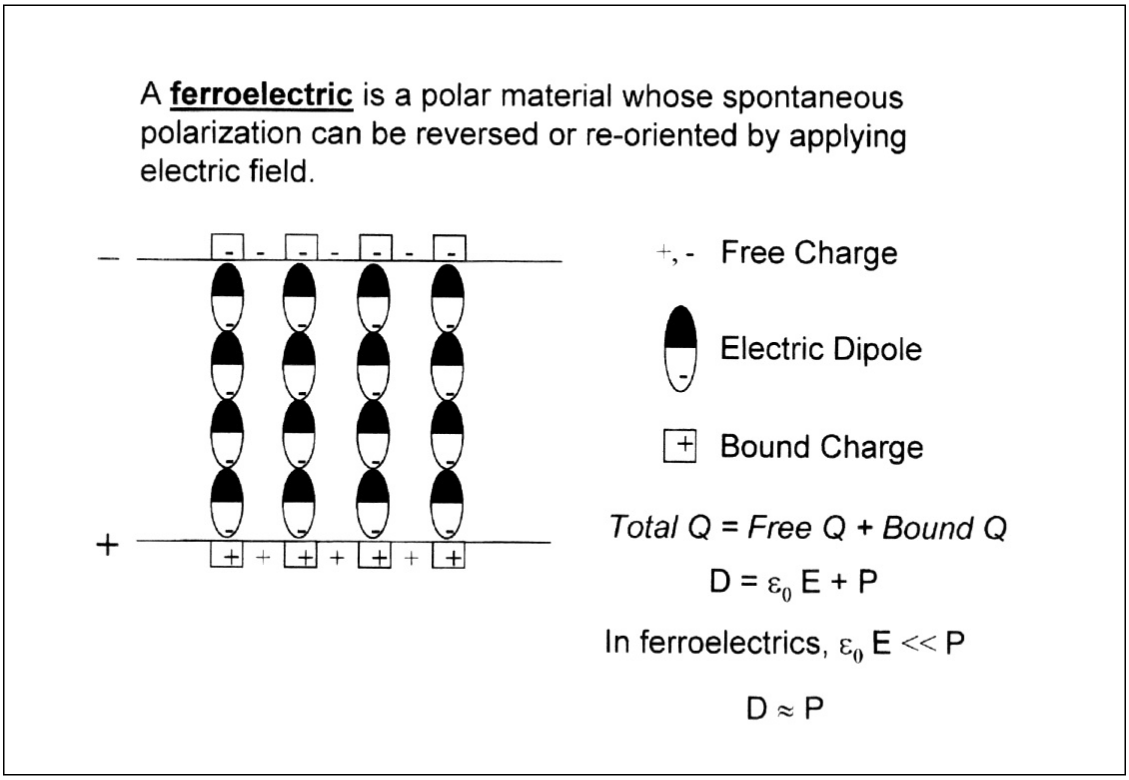

Figure 3-1. A simple illustration of a ferroelectric material (figure courtesy of Symetrix Corporation).

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[25] When an electric potential is applied to a piezoceramic material, its dimensions change. This may be referred to as “motor effect”. Conversely, if an electric charge is produced when mechanical stress is applied, this may be called “generator effect.”

[26] Relatively little work was done with this material, however, until Joseph Valasek began investigating some of its dielectric properties in the early 1920’s [1], [58]. (The paper, *History of Ferroelectrics*, by Eric Cross, reference [58] is an excellent reference for the early history of ferroelectrics.)

In 1920 Valasek presented a paper at the Meeting of the American Physical Society in which he showed a D (displacement current) versus E (electric field) hysteresis plot for Rochelle Salt (Figure 3-1, Figure 3-2). He also noted that P (polarization) versus E (electric field) was analogous to B (magnetic flux density) versus H (magnetic field intensity). He found that he could produce a reorientable spontaneous polarization (Ps) in Rochelle Salt when it was cooled below a certain transition temperature (Tc: Curie Point). By applying an alternating electric field across a sample of this cooled material and tracking the output current, he produced a hysteretic charge loop. [See Figure 3-2]

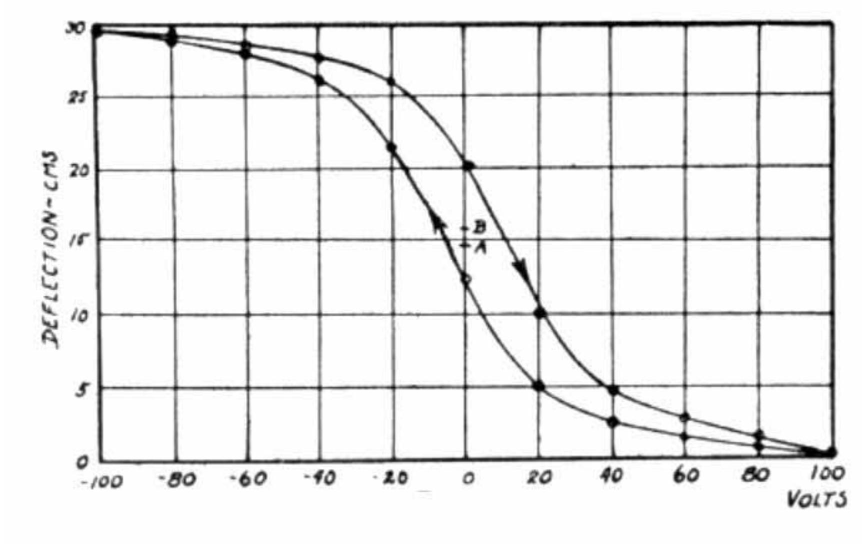

Figure 3-2. Rochelle Salt hysteresis loop

(After Valasek, page 479, reference [4])

(By todays standards, this hysteresis loop was plotted backwards.)

He concluded that polarization is a natural state for Rochelle Salt [2], [4]. This analogy with ferromagnetic properties led easily to the misnomer "ferro"- electric to describe this new class of materials.[27,28] [See Table 3-1]

By definition, today, a material is considered ferroelectric if it has a spontaneous polarization, Ps, which can be reoriented with an electric field across the sample that is larger than the coercive field for that particular material. (By definition, the coercive field is that field where the polarization is reversed and $E = V/d$, where E=field, V=volts and d is the thickness of the capacitor structure.) This reversal is also known as switching.[29]

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[27] Joseph Valasek was born of Czech parents in the United States. He died at the age of 96 in 1993. His PhD thesis, "Piezoelectric activity of Rochelle Salt under various conditions" is dated 1922. [58]

[28] The early designations Seignette-electric and Rochelleelectric, to describe ferroelectric materials, were dropped by 1935.

[29] It should be noted that all ferroelectric materials appear to be piezoelectric, and that all piezoelectric materials appear to be pyroelectric. This would imply that all ferroelectrics are piezoelectric and pyroelectric. The difference, of course, is that ferroelectrics *additionally* possess a reversible, potentially non-volatile macroscopic spontaneous electric dipole moment in the absence of an external electric field.

FERROMAGNETIC	FERROELECTRIC
Ferromagnetic materials show a spontaneous magnetic polarization due to an alignment of magnetic dipoles	Ferroelectric materials show a spontaneous electric polarization due to an alignment of ionic dipoles
Magnetic Domain Alignment Easy Axis Hard Axis	Electric Domain Alignment Easy Axis Hard Axis
Magnetic Hysteresis B Versus H Loop	Electric Hysteresis P Versus E Loop

Table 3-1. Ferromagnetic – Ferroelectric Analogy

(Table courtesy of George Rohrer)

The resulting states for each orientation are generally symetrical at zero voltage, and may be enantiomorphous.[30]

A second ferroelectric material, potassium dihydrogen phosphate (KH_2PO_4 – "KDP"), was discovered by G. Busch and P. Scherrer in 1935. This, in turn, was followed by some of its isomorphs (ammonium dihydrogen phosphate and potassium dihydrogen arsenate) [6].[31]

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[30] Enantiomorphous: The resulting states are mirror images of each other.

[31] Isomorphs are materials with close similarity in crystalline form but with different compositional elements.

The third major ferroelectric substance, barium titanate, $BaTiO_3$, was discovered sometime after 1940 (probably by A. Von Hipple at MIT). We know that many independent researchers in Russia, England, Holland, Japan and Switzerland worked on this material between 1940 and 1945. Unfortunately, all publications concerning this material were security classified in the United States during this time period. An excellent accounting of this research, however, is given by A. Von Hippel in a paper published in Modern Physics in 1950 [8]. It is interesting to note that von Hippel does not claim credit for discovering the ferroelectric properties of barium titanate, at least in this paper, but that others imply that he should be given that credit [58].

Barium titanate was the first *ceramic* material that exhibited ferroelectric behavior. This proved that ferroelectricity could exist in simple oxide materials, and that it was not always associated with hydrogen bonding (such as found in such water soluble compounds as Rochelle Salt, potassium dihydrogen phosphate, ammonium dihydrogen phosphate, etc.). Barium titanate is a member of the perovskite family. This crystal family designation is based on the atomic configuration of the mineral perovskite, $CaTiO_3$ (Figure 3-3). Following the barium titanate discovery, this same crystal family has since yielded over 250 pure materials and many more mixed systems that are also ferroelectric.[32]

[32] It is estimated that there are now approximately 2000 known ferroelectric materials. It is interesting to note that even ice exhibits ferroelectric properties [7].

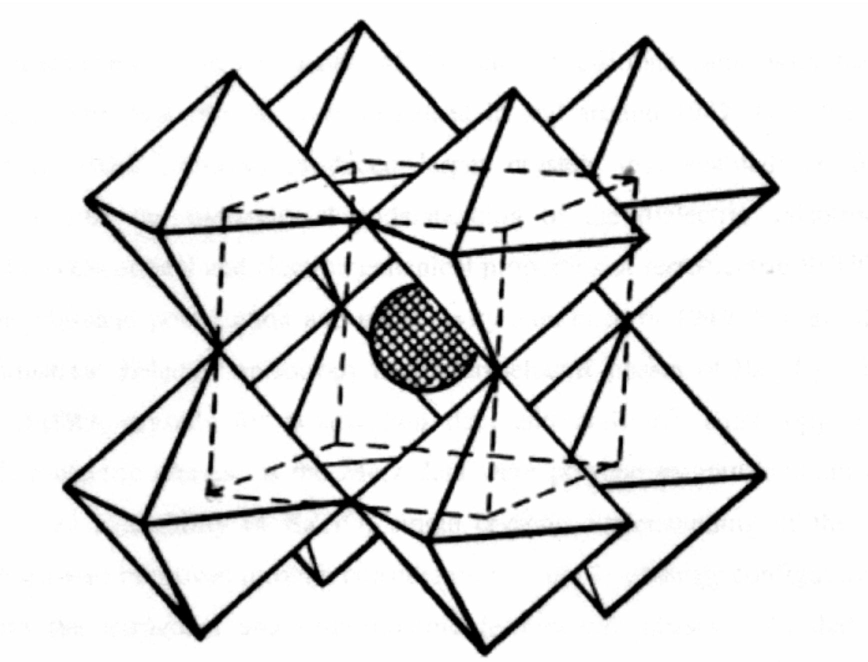

Figure 3-3. Basic perovskite structure of $BaTiO_3$ with the Ba ion in the center of the cell and Ti ions inside the oxygen octahedra. (After Randall, reference [54])

3.2. The single crystal ferroelectric memory

In 1952, J. R. Anderson proposed construction of the first non-volatile memory device using ferroelectric barium titanate [11], [12]. This device consisted of a 100 micron slice of single-crystal barium titanate with an x-y addressing electrode matrix. An electric field was used to switch, or “write”, each ferroelectric cell into either a positive or negative polarisation state. His proposed device was built, with sevaral design variations, by AT&T, Ford, IBM and Westinghouse during the 1950’s (Figure 3-4).

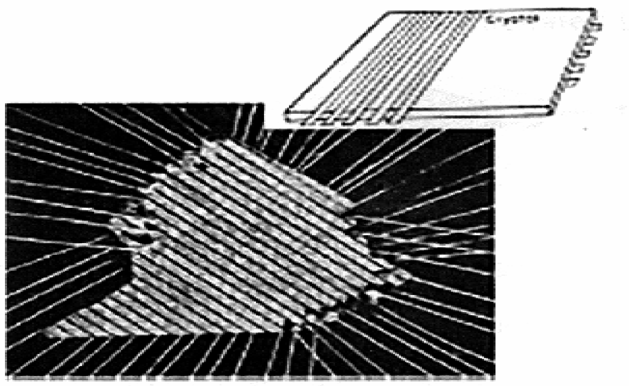

Figure 3-4. Typical electrode arrangement for a 100 micron thick barium titanate crystal memory, circa. 1955

(After Daglish, Pg. 23, Reference [11])

The basic principle of a ferroelectric (matrix) memory was demonstrated, but none of these devices proved to be commercially practical for a number of reasons. Preparation and selection of the uniformly thin pure crystal slices was very expensive. Regardless of how the conductors were configured, excessive cross-talk between adjacent address lines could not be eliminated, and single crystal slices could never be thinned to the point where reasonably small write voltages could be achieved [13].

In 1962, James Nolta and Norman Schubring of General Motors Research Laboratories in Warren, Michigan, reported that, based on the earlier work of Sawada, Nomura, Fujii and Yoshida with sodium nitrate, they (Nolta and Shubring) had discovered ferroelectricity in room temperature potassium nitrate [9], [14]. In their experiments, Nolta and Schubring melted reagent grade potassium nitrate on a copper substrate which became the bottom electrode of a capacitor-like structure. For top electrodes they tried mercury, metallic foils and silver paint which they applied while the potassium nitrate was still molten. Some of their KNO_3 sandwich structures were as thin as 2×10^{-3} cm. They achieved extremely symetrical hysteresis loops with their devices but noted that all ferroelectric properties quickly diminished in the presence of moisture.. (They, of course, realized that, like many of the earliest known ferroelectric materials, potassium nitrate was water soluble.)

3.3. The first polycrystalline thin film ferroelectric memory

In 1968, George Rohrer, who was then a graduate student at Michigan Technological University in Houghton, Michigan, succeeded in building a large number of very thin (750 Angstrom thick) potassium nitrate capacitors in a vacuum chamber. Utilizing a modified metal evaporation system, he evaporated KNO_3, onto gold electroded glass substrates and then evaporated gold top electrodes and silicon *monoxide* passivation glass (through shadow masks) onto the KNO_3 while the devices were held under vacuum (Figure 3-5). This process essentially eliminated the moisture problem and resulted in thin film capacitors with excellent ferroelectric memory properties [15], [16].

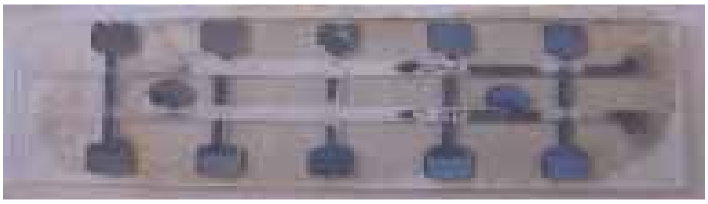

Figure 3-5. George Rohrer's Thin Film KNO_3 Ferroelectric Memory built on a glass slide with a shadow mask vacuum deposition process, circa. 1968 (Photo, courtesy of George Rohrer)

Rohrer quickly patented his invention(s) and organized a small company in Sault Ste. Marie, Michigan with the objectives of manufacturing and selling "raw" thin film ferroelectric memories.[33]

[33] Rohrer's company was named Technovation Corporation and was financed by private investors out of Detroit, Michigan.

3.4. McMillan's cubic integration

McMillan, the author of this thesis, met George Rohrer in 1973. After visiting Rohrer's laboratory in Sault. Ste. Marie, McMillan soon realized that polycrystalline and randomly oriented films could replace the highly structured crystalline materials previously considered for memories. He also came to the conclusion that Rohrer's raw ferroelectric memory array (with its external decoding arrangement) could possibly become the key component for a non-volatile, random access memory device with all the required power supplies, decoding circuitry and I/O capabilities built into a "cubically integrated" structure. It seemed obvious to McMillan that it would be less costly and technologically more feasible to build integrated circuits as three dimenensional arrays with active and passive components deposited in layers above a substrate, rather than following Moores law and continuously crowding more and more electrical components into smaller and smaller planar structures [20], [66].[34]

[34] Gordon Moore predicted in 1965 that the transistor count per chip would double about every two years. He apparently based his prediction on the fact that the number of transistors per chip in 1961 was about four and by 1965 the number per chip was about 200. The actual growth rate, after nearly forty years of data, now appears to double about every eighteen months.

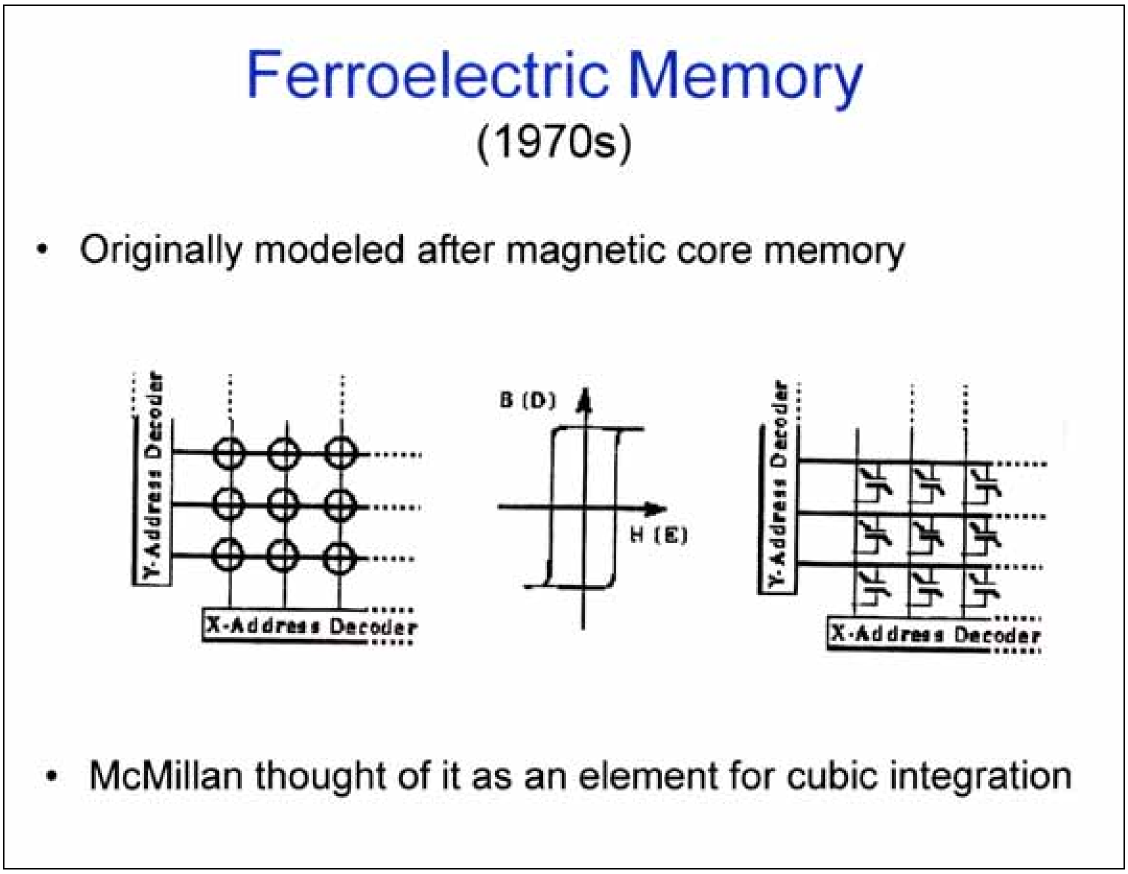

Figure 3-6. Ferroelectric versus magnetic core memory

After reference [68]

McMillan became so enamored with Rohrer's ferroelectric memory that he took a leave of absence from Motorola, his employer at that time, and moved to Sault. Ste. Marie to work with Rohrer on his "new" technology.

3.5. Ferroelectric capacitor C-V plots

Based on his earlier research on capacitance versus voltage (C-V) testing of metal-oxide-silicon (MOS) devices and his seminal paper on C-V modeling (*MOS C-V Techniques for IC Process Control*, Appendix E), McMillan developed a C-V test for switching metal-ferroelectric-metal capacitors. A typical C-V plot of a potassium nitrate (low dielectric constant) ferroelectric capacitor during switching is shown in Figure 3-7.

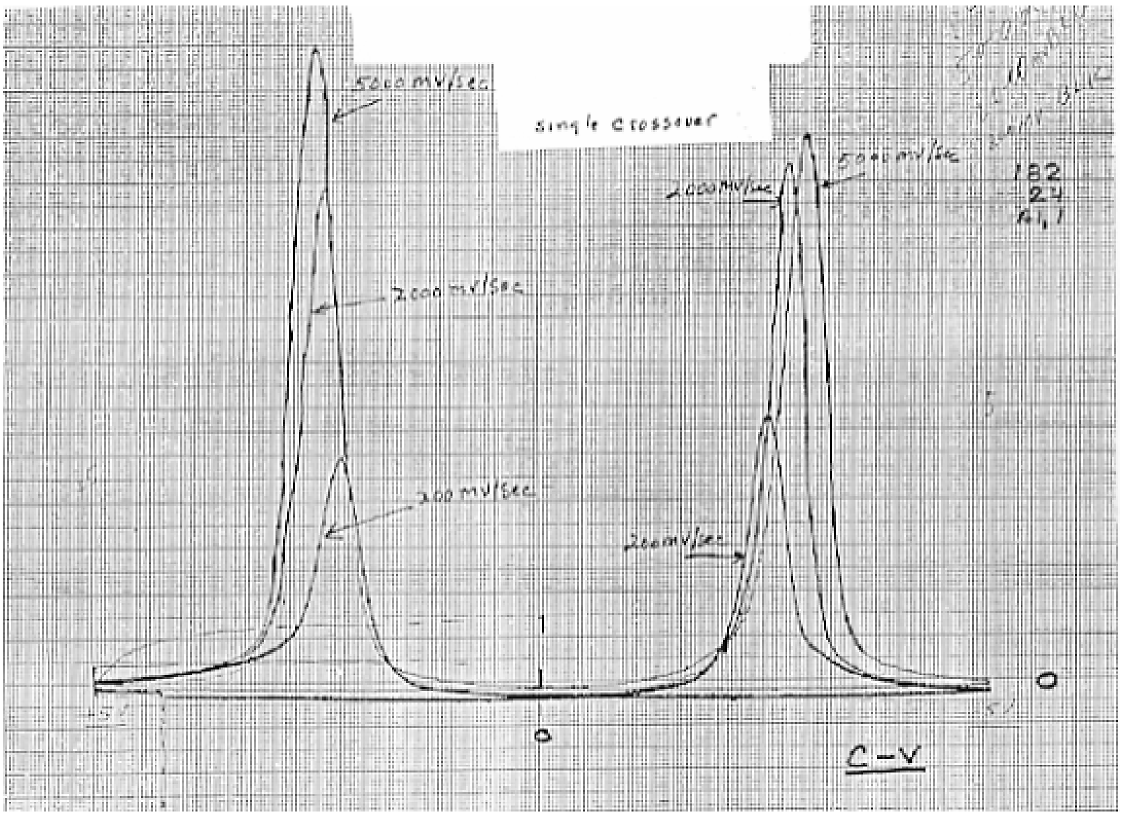

Figure 3-7. Capacitance/Dielectric constant versus voltage for a ferroelectric capacitor

In figure 3-7 it is quite apparent that the dielectric pulse amplitude is proportional to the voltage ramp rate and that the (measured) capacitance value changes dramatically as the switching ferroelectric induces varying charge pulses on the capacitor electrodes.

We note the following for any parallel plate capacitor:

CV=Q (**C** = capacitance, **V** = voltage, **Q** = charge.)

If the dielectric medium between the electrodes is linear then:

$$C\frac{dV}{dt} = \frac{dQ}{dt} = i_{cap}$$

However, if the dielectric medium is also ferroelectric and switches from one state to the other during a voltage pulse then we have:

$$C\frac{dV}{dt} + V\frac{dC}{dt} = \frac{dQ}{dt} = i_{total}$$

where $$C\frac{dV}{dt} = i_{cap}$$

and $$V\frac{dC}{dt} = i_{switch}$$ (due to switching ferroelectric)

Figure 3-8 shows the relationship between (a) P vs. E, (b) C vs. V and (c) I vs. V for a ferroelectric capacitor**.** It is generally believed that McMillan was the first person to develop such a method for plotting the changing dielectric constant of a ferroelectric capacitor during ferroelectric switching. This test not only became standardized at Symetrix Coporation many years later, but also provided the unique and critical data needed to understand and solve the fatigue and retention problems associated with the FeRAM.

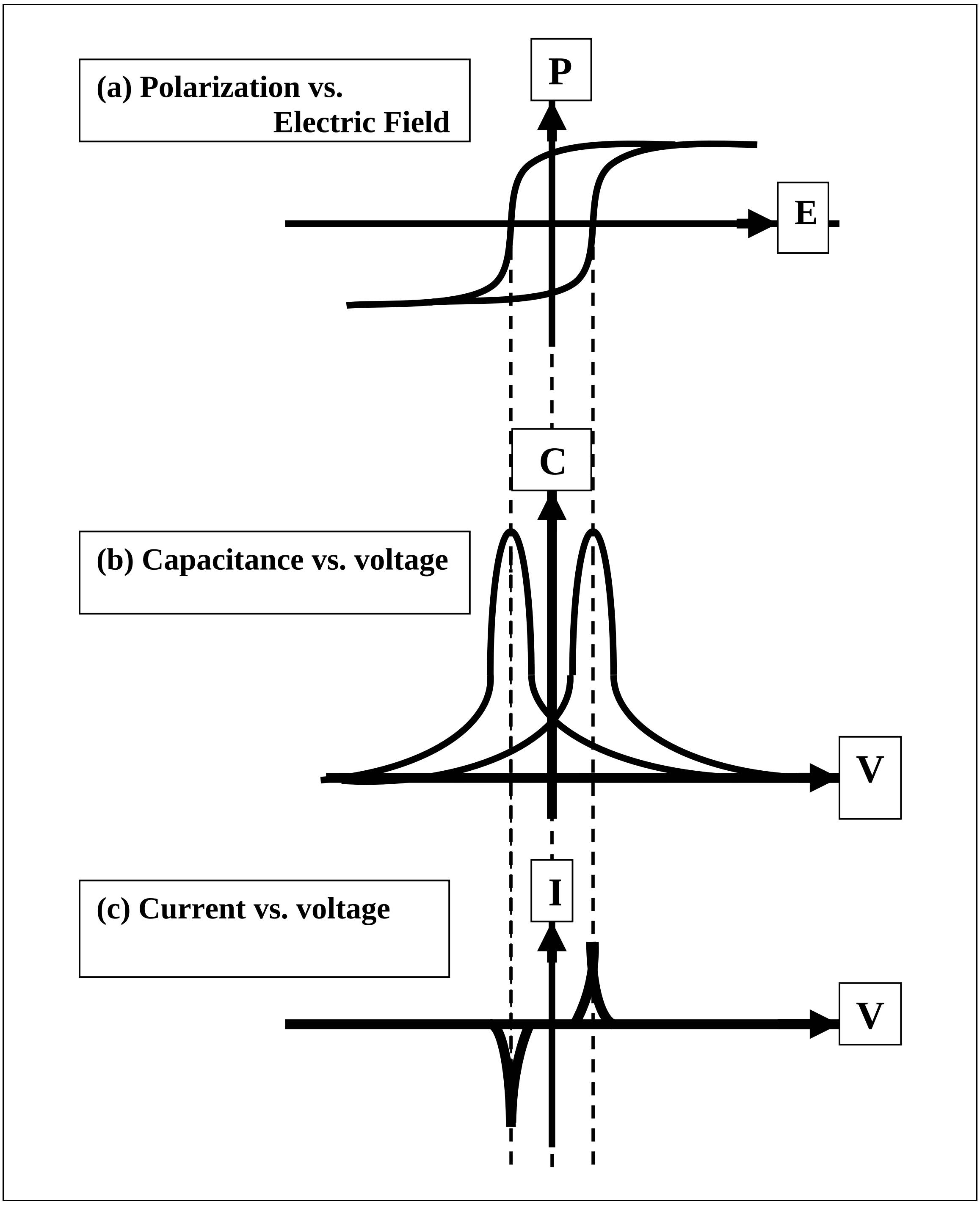

Figure 3-8. The relationship between (a) P vs. E, (b) C vs. V and (c) I vs. V for a ferroelectric capacitor.

3.6. Integrated ferroelectric memory

The first integrated ferroelectric memory device (with active components – ferroelectric switches - that were not dependent on single crystal silicon) was finally disclosed by McMillan to Motorola in 1976 (Appendix A).[35] Figure 3-9 shows the abstract and primary drawing from the patent that was ultimately filed several years later.

Motorola sent several technical and legal people to Technovation to investigate Rohrer and McMillan's integrated memory. They concluded that the technology was valid and quite interesting, but not commercially viable at that time. Motorola declined to invest in any way, which led McMillan to depart from Motorola soon thereafter (in 1976).

Unable to obtain additional funding, Rohrer was forced to close operations in Sault. Ste. Marie, and seek other employment in southern California. McMillan moved to Silicon Valley where he became employed by American Micro Systems. Rohrer and McMillan continued close communications with each other and both continued to seek, unsuccessfully, reliable and ethical investors for their integrated ferroelectric memory.

[35] This should dispel questions concerning the identity of the inventor of the integrated ferroelectric memory.

ABSTRACT

A monolithic semiconductor integrated circuit-ferroelectric device is disclosed together with the method of manufacturing same. The ferrelectric device preferably consints of a layer of stable ferroelectric potassium nitrate disposed between electrical contacts positioned on opposite surfaces of the ferroelectric layer. The ferroelectric layer has a thickness of less than 110 microns, and preferably falling within a range of from 100 Angstrom units to 3,000 Angstrom units. The process of manufacturing the monolithic structure is multi-stepped and is particularly adapted for fabricating a potassium nitrate ferroelectric memory on a semiconductor integrated circuit.

26 Claims, 16 Drawing Figures

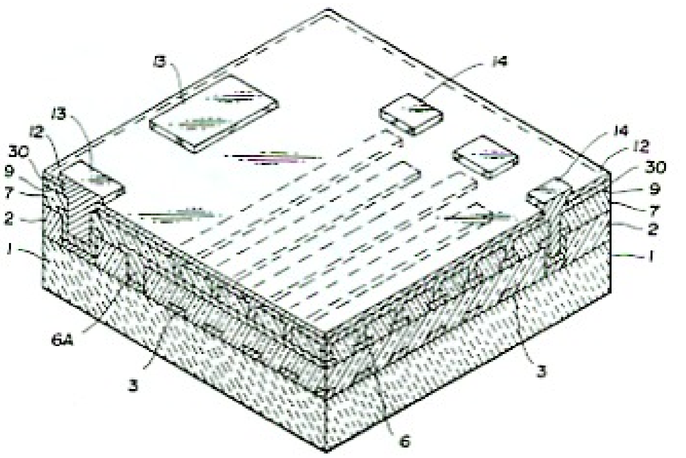

Figure 3-9. Drawing and abstract from McMillan's patent for first integrated ferroelectric memory device

In 1977, a former employee of American Micro Systems (who shall remain un-named), unethically copied McMillan’s 1976 Motorola memo (Appendix A) and used it to file for, and obtain, two patents without referencing McMillan.[36, 37] Following extended litigation and the expenditure of thousands of dollars in legal fees, (paid by McMillan, Rohrer and Ramtron Corporation) new patents were issued and ultimately assigned to Ramtron Corporation. (See listing of patents at end of thesis).

[36] It is interesting to note that McMillan's name, initials (on each page) and disclosure dates were all plainly visible on the documents sent by the perpetrator to the U.S. Patent office. The Patent Office, however, ignored the evidence (and proof) of McMillan's invention(s) and issued the patents to the perpetrator. The attorneys on all sides of the ensuing legal proceedings were extremely well compensated, the perpetrator was never prosecuted and the inventor, McMillan, lost thousands of dollars in the process.

[37] Reference McMillan's Stagnation Wall in section 2.3.

3.7. The Founding of Ramtron Corporation

In 1983, an investment group out of Australia contacted Rohrer and offered to buy out Technovation and start a new company. Rohrer asked McMillan, who was then a manager at Honeywell, to assist him (Rohrer) with the Australian venture group negotiations. These discussions finally led to McMillan's resignation from Honeywell, and McMillan's friend, Dr. Carlos Paz de Araujo, a professor at UCCS in Colorado Springs, joining the effort to form Ramtron Corporation. (Note that the name Ramtron is derived from the names Rohrer, Araujo and McMillan.) Following several discussions and agreements between UCCS, the Australian investors and the founders, Ramtron Corporation was incorporated in 1984 and began operations in a UCCS laboratory in May of that same year (note Figure 3-10).

The Australian investors hired a new management team who had previous experience in the IC industry but very little knowledge or experience with ferroelectric materials or devices. Ramtron's new managers decided to change the ferroelectric material from potassium nitrate to lead zirconate titanate (PZT) and the founders were assigned to technical supporting roles.[38] It was impossible to convince George Rohrer that he should work on anything other than the potassium nitrate that he had

[38] Ramtron announced at the ISSCC the development of a 256-bit PZT memory with 4 micron design rules in 1988 [64].

pursued for over sixteen years. Obviously, Rohrer had reached his stagnation wall!

It soon became obvious that the investors, the new managers and the founder scientists were on very different paths. Ramtron purchased Technovation's intellectual property and George Rohrer retired to the upper peninsula of Michigan, where he later died.[39] McMillan and Araujo left Ramtron Corporation in 1986.

[39] George Rohrer died of cancer, at age 61, in Sault Ste. Marie, Michigan, March 9, 1997. Rohrer's contributions to the technology of thin film ferroelectric memories were very significant. Among other things, he proved that viable memory devices could be built with polycrystalline materials. He also proved conclusively that such devices exhibited excellent electrical characteristics down to 75 nm in thickness.

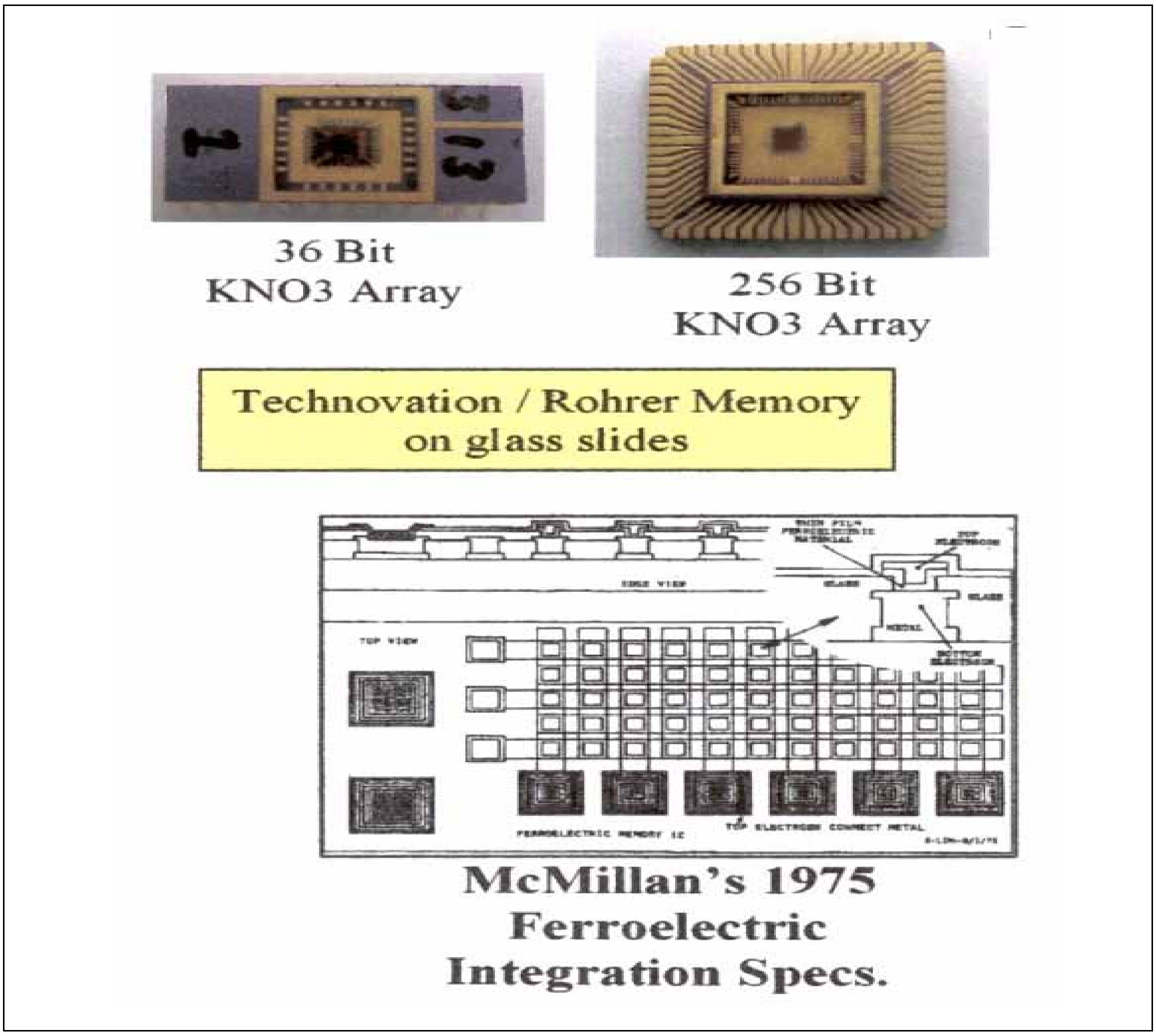

Figure 3-10. The initial intellectual property assets of Ramtron Corporation.

3.8. Symetrix Corporation

Symetrix Corporation was co-founded by McMillan and Araujo in 1986. With no capital, other then their personal savings, their startup business strategy was quite simple and centered around several areas of concern that were obviously related to their Ramtron experiences. Although never written into any kind of formal business plan, the corporate founders were highly motivated and actually driven emotionally by the strategic elements shown below in Figure 3-11.

(1) Minimize the number of outside investors.
(2) Maximize the founders' ownership.
(3) Remain a "Privately Held Corporation" as long as possible.
(4) Stay away from outside "Entrepreneurs" and venture capitalists.
(5) Provide initial funding with SBIR (U.S. Government) contracts.
(6) Seek working relationships with large companies – rather than competing with them.
(7) Remain an intellectual property based company, selling licenses to other companies and collecting royalties for their patents.

Figure 3-11. Symetrix Business Strategy

By most standards, this was not the way to start a company. Most experts in the field teach that writing a comprehensive business plan is essential to initiating any corporate activity. For instance, Michael Baird, in his book *Engineering Your Start-Up*, states quite unequivocally:

> *"Other than your last will and testament, the most important document you will ever write is your business plan. A business plan gives birth to your start-up. It enables you and your team to envision and plan how the business will be run and to raise funds."* (Baird, page 108, reference [60].)

Obviously, McMillan and Araujo were being driven by factors that surpassed common sense. Their "business strategy", however, became effective immediately. They applied for and won several SBIR contracts with the U.S. Government.[40] The proceeds from these contracts were sufficient to finance Symetrix for several years until they were able to negotiate research contracts with a number of large corporations.

Their research strategy for the new company was not quite as simple as their business strategy. It had now become obvious that devices built with either potassium nitrate or PZT could not meet commercially viable fatigue and retention criteria. A thin film ferroelectric material needed to be developed that could withstand the rigors of continuous switching over long periods of time while still exhibiting solid data retention, fast speed and low leakage. The search for a better (fatigue free) material quickly became the critical element of the research plan.

For any ferroelectric product or device to become commercially viable, the ferroelectric material and related structures must also be manufacturable. The problem was that most of the hundreds of possible ferroelectric material candidates had very complex stoichiometries that could neither be easily synthesized, nor deposited as thin films with existing equipment. Device models and testing methods for ferroelectric thin film devices were essentially non-existant. Extensive device theory was obviously needed to move the technology forward. Figure 3-12 shows a simplified flowchart of the research strategy that eventually drove the company forward, resulting in the portfolio of McMillan authored and co-authored patents shown in Appendix B.

3.9. The New Management Approach

Program and project management proceedures were implemented as soon as the first SBIR contract was received and the same basic proceedures continued to be used throughout the many years of Symetrix Corporate operations.

From the initial formation of their management strategy, McMillan and Araujo were very concerned with the recruitment and development of a small, efficient and dedicated heavyweight team that could assume responsibility for simultaneously running multiple projects.

It is interesting to note that, while defining such a heavyweight team, Clayton Christensen, in his book, The Innovator's Dilemma, states:

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[40] SBIR: Small Business Innovative Research.

"...They define a heavyweight team as one in which team members typically are dedicated and colocated. The charge of each team member is not to represent their functional group on the team, but to act as a general manager - to assume responsibility for the success of the entire project, and to be actively involved in the decisions and work of members who come from each functional area. As they work together to complete their project, they will work out new ways of interacting, coordinating, and decision-making that will come to comprise the new processes, or new capabilities, that will be needed to succeed in the new enterprise on an ongoing basis....."

(Christensen, The Innovator's Dilemma, page 209, reference [25].)

Christensen seemed to know exactly what we wanted!

Rather than recruiting experienced, industry-savvy, engineers (who would probably have many preconceived ideas from their previous work experience), we knew that we really were looking for people who would become associates, not regular employess driven by traditions and old ideas, but rather driven by knowledge. As Drucker stated in his book *Management Challenges for the 21st Century* (page 18, reference [27]):

"....Even if employed full-time by the organization, fewer and fewer people are "subordinates"- even in fairly low-level jobs. Increasingly they are "knowledge workers." And knowledge workers are not subordinates; they are "associates." For, once beyond the

apprentice stage, knowledge workers must know more about their job than their boss does-or else they are no good at all. In fact, that they know more about their job than anybody else in the organization is part of the definition of knowledge workers."

We were looking for "knowledge workers"! Eventually we hired several top notch Ph.D.'s, fresh out of school, who were extremely willing to learn and ready to cooperate with each other. None of these people considered themselves inventors and none of them had patents listed in their work experience. Every Symetrix employee was required to enter into an agreement that assigned to Symetrix Corporation all inventions and patents derived during their term of employment. This, of course, implied that most new inventions should result from teamwork and that such inventions would necessarily be patented with co-authors rather than single authors. In a rather subtle way, this strategy tended to minimize the inventor stagnation wall problem before it could became a consideration of the individual inventors.

The management approach adopted by Symetrix was quite simple and followed, to a considerable extent, the Plan, Do, Check, and Act (P-D-C-A) decision-making process outlined by R. Ray Genani in his book, *Management of Technology and Operations* (pages 325 - 326, reference [44]).

The Symetrix team, however, changed slightly Genani's basic P-D-C-A process and introduced a general philosophy that every project was to 'begin with the end in mind' and work backwards from the end objectives. With the end goal(s) clearly defined and understood, project flow charts and schedules were implemented using various software tools such as Microsoft Project, Project Management Pro and various other Gantt Chart and Pert Chart management programs. By defining individual tasks from the perspective of desired results and working backwards, activities not directly contributing to the end goal(s) were eliminated.

Following closely the Nominal Group Technique (NGT) outlined by Geheni (pages 352 -355, *Management of Technology and Operations* [44]), all team members contributed to the development of project flows, patents applications, risk assessments, critical path determinations and personnel assignments. As each project/program advanced, all Gantt charts, program assessments, process data, etc., were reviewed, corrected and updated on a weekly basis.[41] All engineers and scientists were required to produce written weekly, bi-weekly and monthly progress reports on all of their activities. These reports were used for project status visibility and identification of issues. Very detailed quarterly technical reports were prepared for all customers giving insight into achievements. These reports also identified past and current technical and management problems and offered strategies to overcome difficulties.

[41] Gantt charts were developed by Henry L. Gantt early in the twentieth century [40].

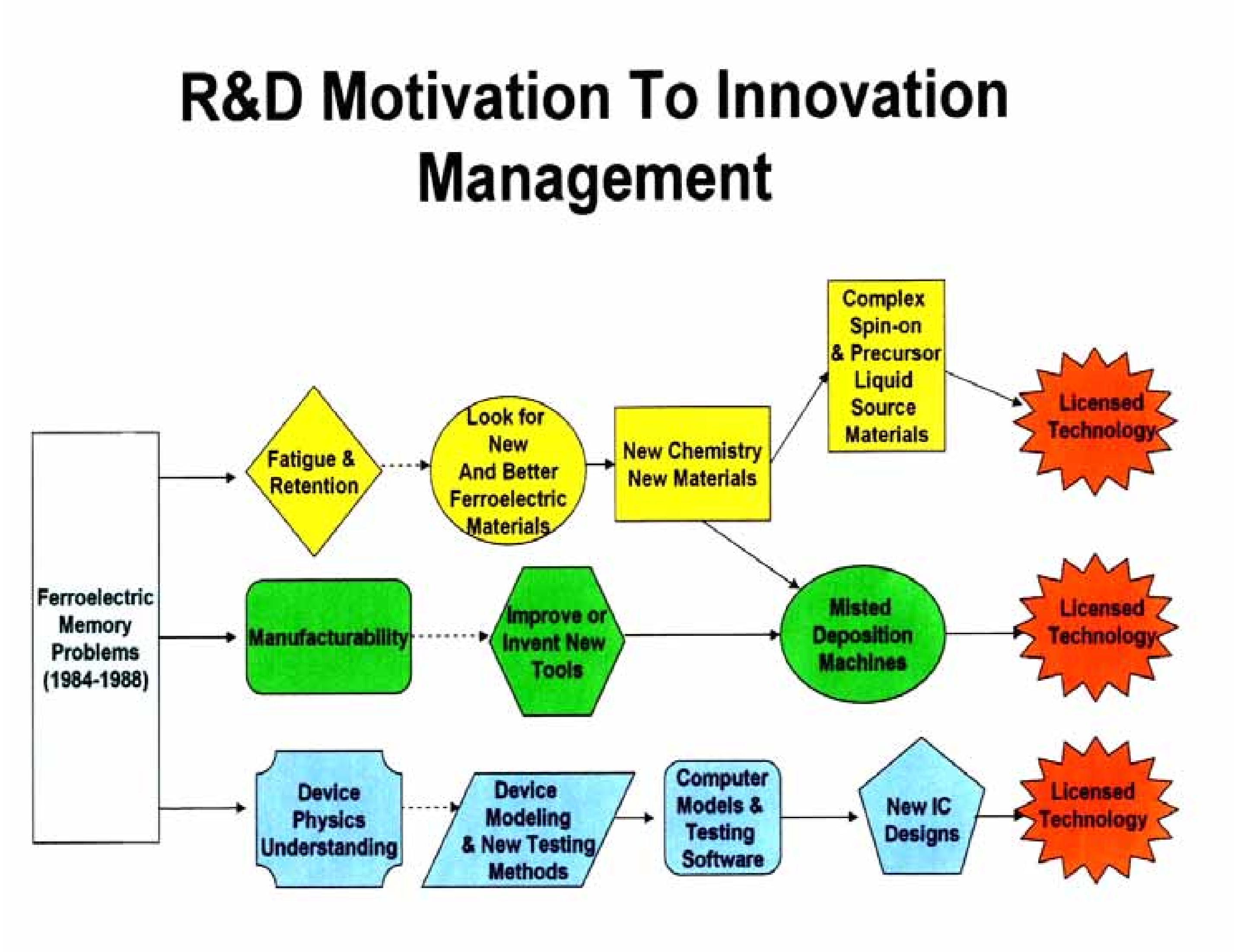


Figure 3-12. Symetrix Research Strategy

3.10. Material synthesis

To address the material synthesis problems, McMillan resorted to his prior experience with sol-gel (solution-gelation) chemistry. Sol-gel, which probably originated in Russia during the 1940's, is based on the various reactant species of hydrolyzed metal alkoxides and alcohol.

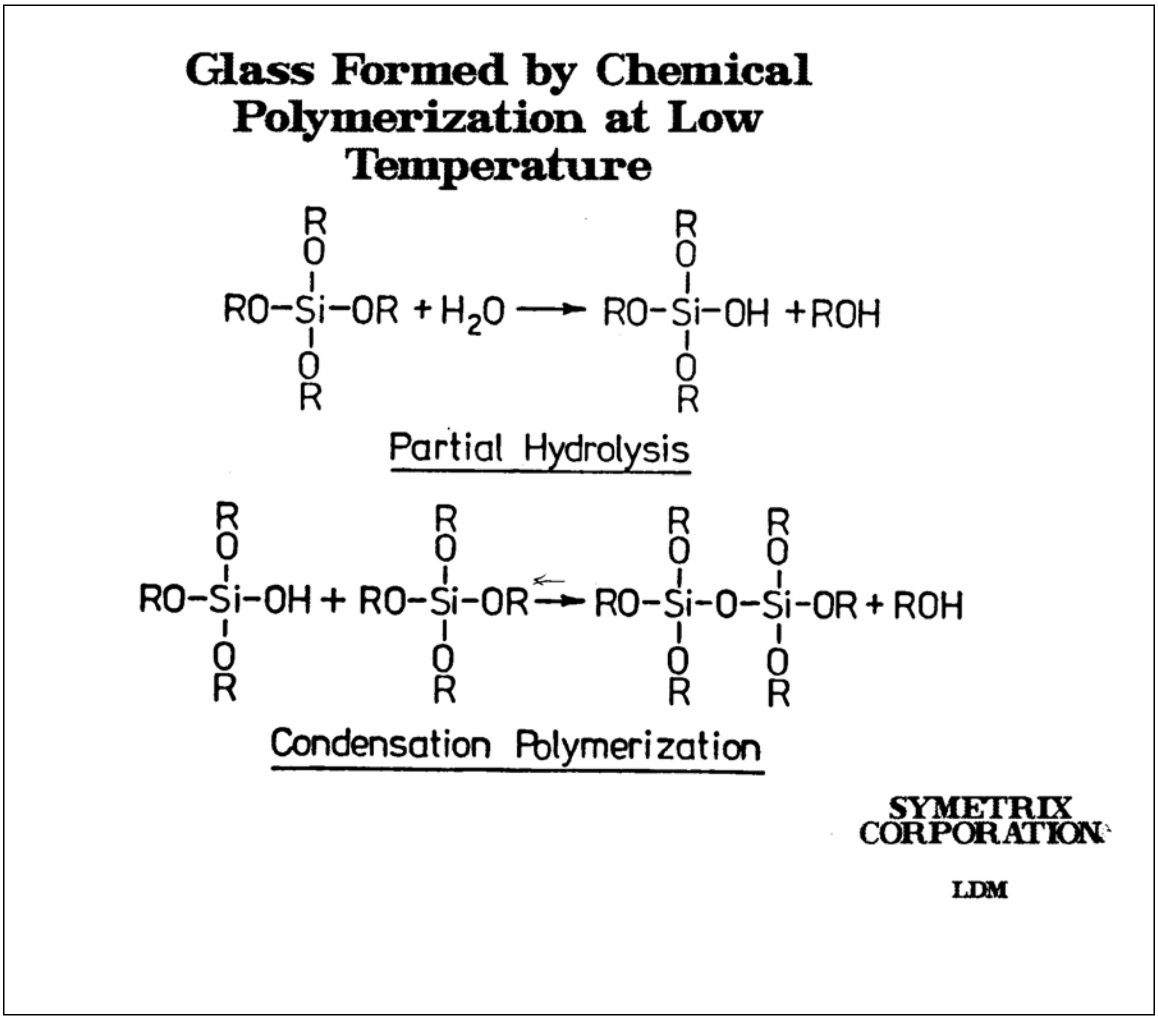


Figure 3-13. Sol-gel polymerization reactions.

Such chemistries produce preciptant gels that may be applied to smooth surfaces and dried to form glass-like layers (see figures 3-13, 3-14, 3-15 and 3-16). Such processes had been used in the semiconductor industry for several years to form passivation layers on silicon substrates.

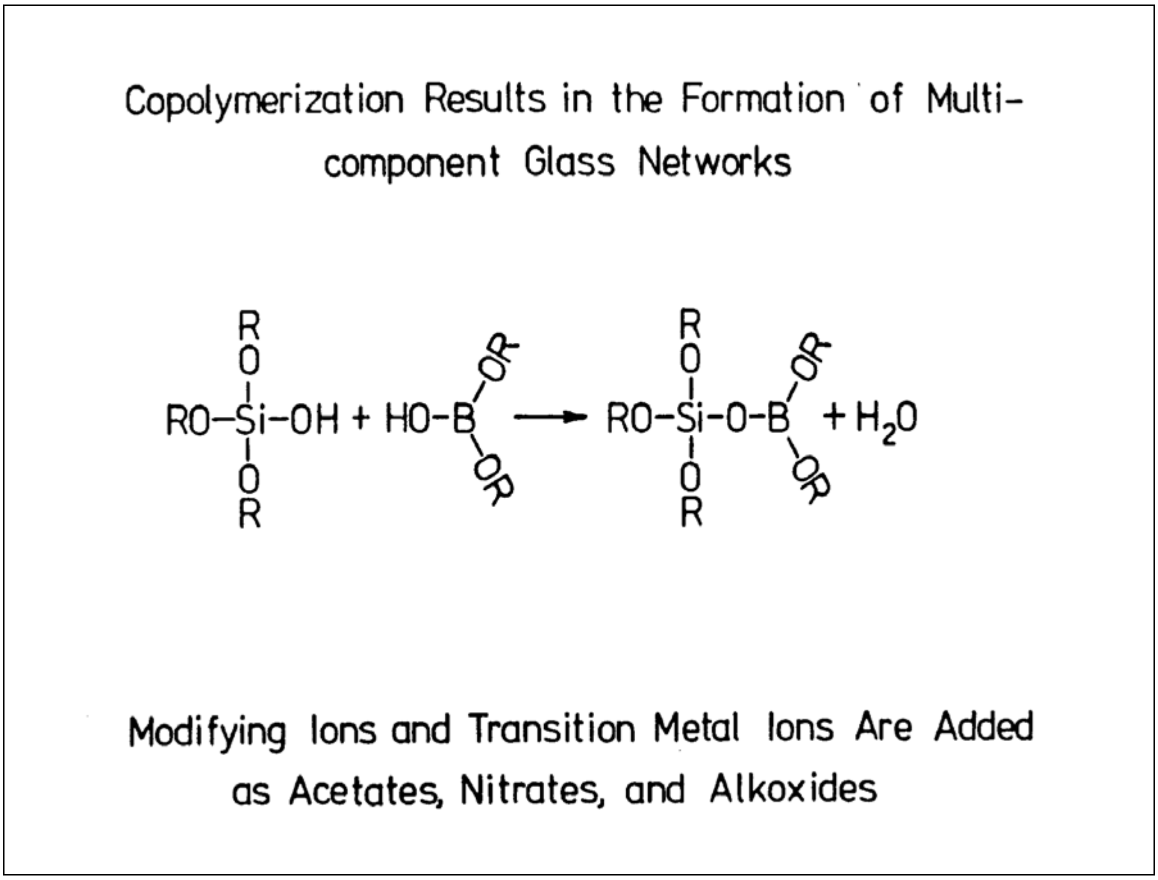


Figure 3-14. Sol-gel copolymerization of multicomponent glass networks.

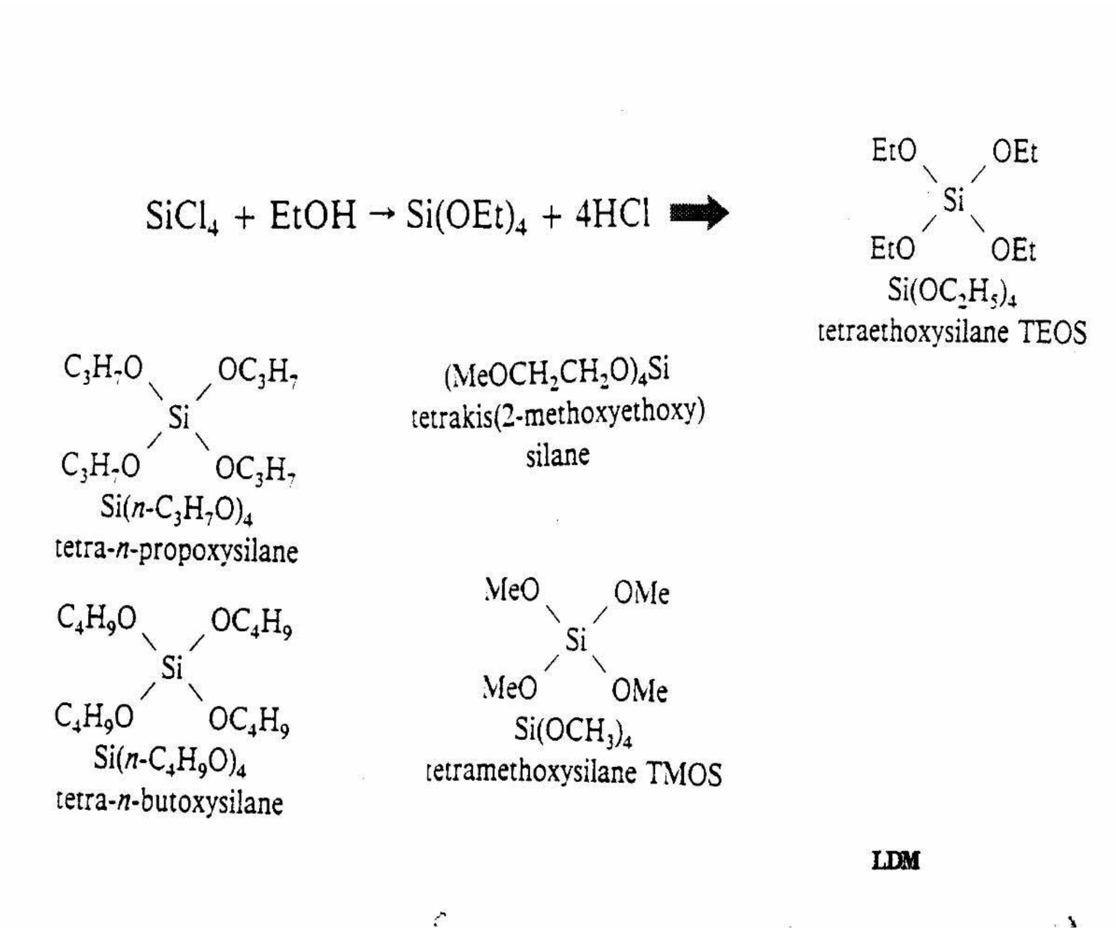
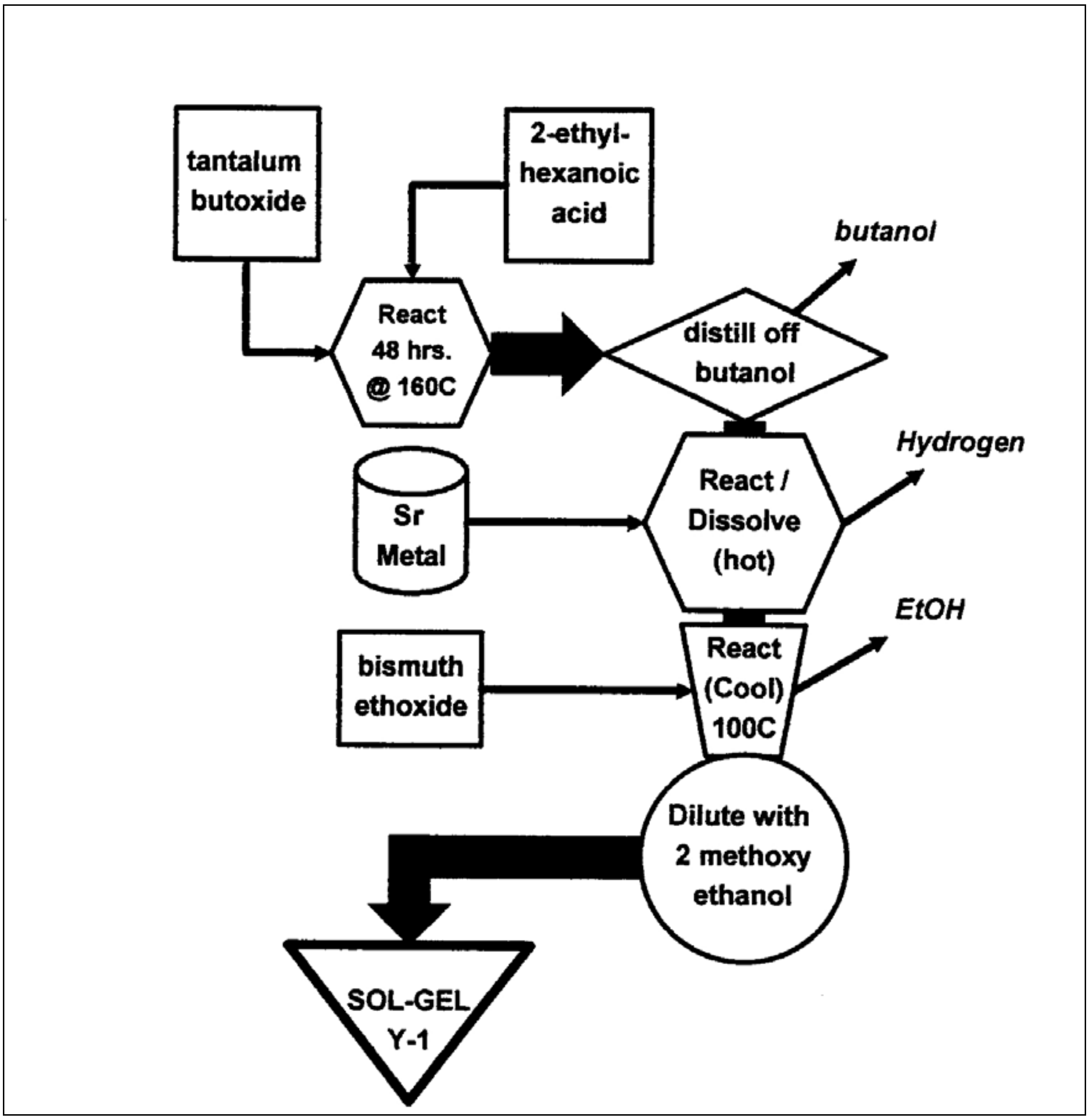


Figure 3-15. Typical precursors.

Figures 3-16 and 3-17 outline process flows for various modified sol-gel and metal-organic-decomposition (MOD) chemistries that are referenced later in this thesis.



3-16. Process flow for sol-gel Y-1.

This enabled the synthesis of a rather large number of complex ferroelectric materials with multiple stoichiometries in various solvents.

These liquid solutions were easily applied to silicon wafer substrates via spin coating using a standard IC photoresist spinner. The films hydrolized, forming M-O-M (metal-oxide-metal) bonds, resulting in stoichiometrically controlled ferroelectric materials

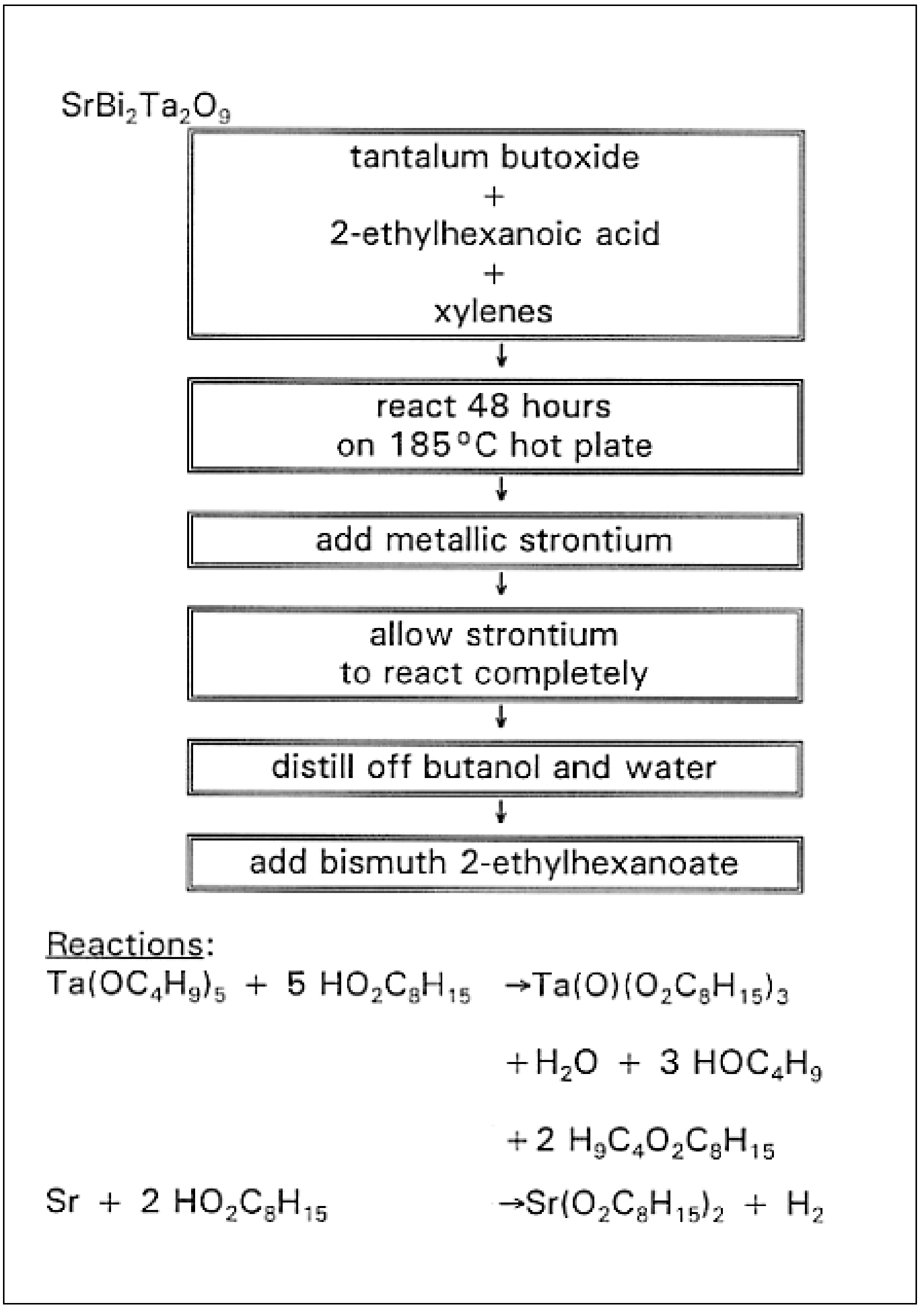


Figure 3-17. Process flow for modified sol-gel + MOD SBT process

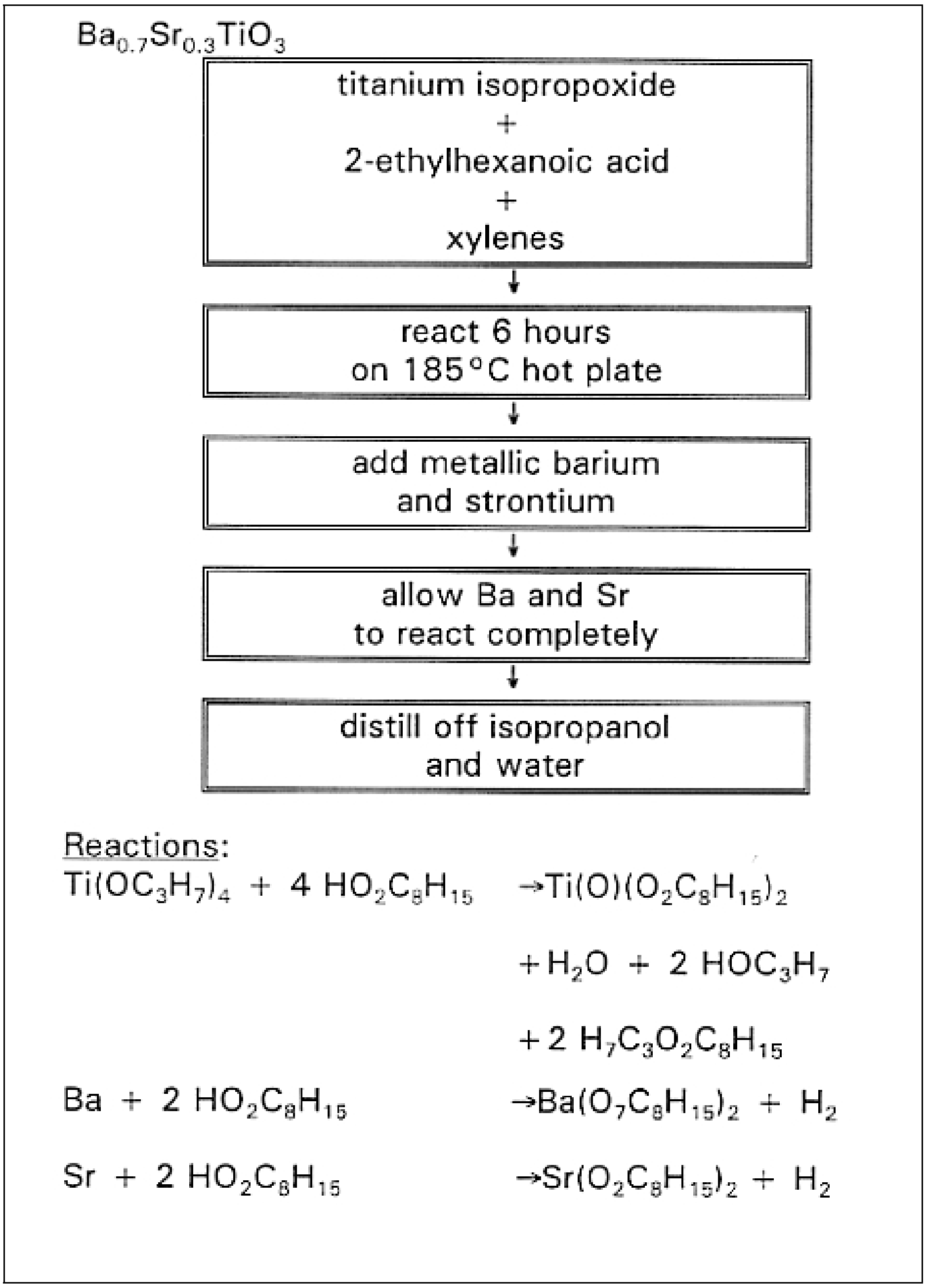


Figure 3-18. Process flow for Barium Strontium Titanate precursors.

By coating wafers patterned with bottom electrodes, annealing (crystallizing) the films and then depositing (and patterning) top electrode metal, thousands of ferroelectric capacitors, with different materials, were built and tested during the initial phases of Symetrix research.

Liquid sol-gel, however, is very moisture sensitive, so gelation and precipitation occur during storage. Gelation rates (k_{Ba}, k_{Sr}, k_{Ti}, etc.) vary with the complexity of the metal hydroxide bonds, ambient temperature and light exposure. Different metal compounds therefore precipitate at different rates resulting in non-stoichiometric solutions and uncontrollable film properties Figure 3-19.

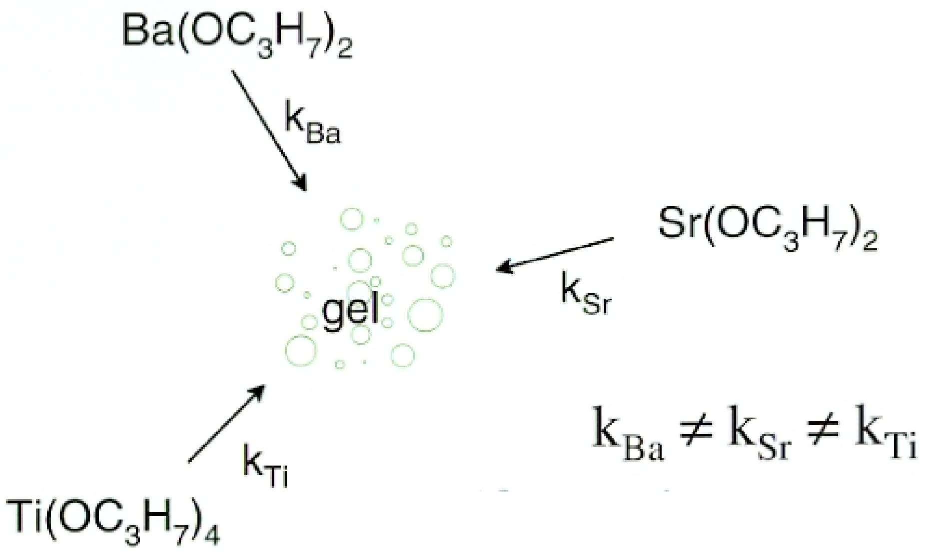


Figure 3-19. Gelation of multiple component solutions Nonuniform microaggregates result in uncontrollable stoichiometries.

McMillan became aware of another chemical synthesis technique being developed under U.S. government contract at the University of Illinois. The scientists there were using a neodeconoic acid/solvent decomposition process that prevented hydrolization of metal ions in solution. Using a solvent exchange technique, McMillan and the Symetrix team were able to merge the two chemistries such that the moisture/hydroxide problem was eliminated and a new enhanced metal organic decomposition (EMOD) chemistry was invented (Figure 3-20). Millan's solvent exchange process was then used by the Symetrix team to encorporate over fifty elements into a common solvent system. This, in turn, allowed the mixing of any of these elements with all other elements in the same solvent system (Figure 3-21).

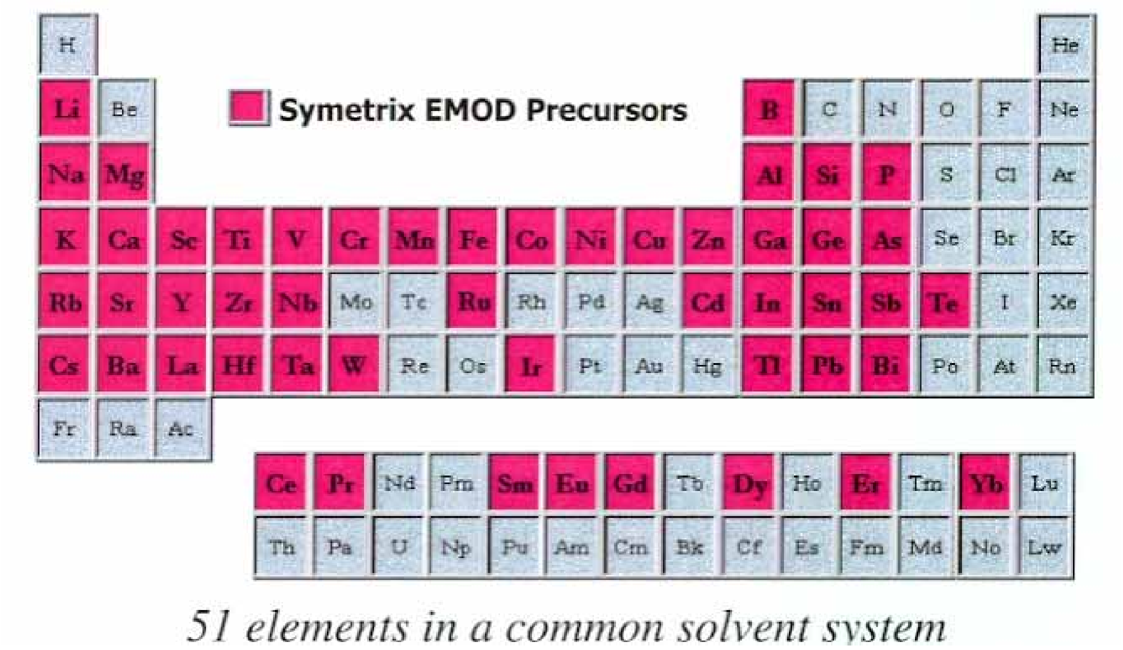


Figure 3-20. EMOD precursor system. All elemental precursors are miscible with all other precursors in the same solvent system.

The new chemical process became the basis for all future material synthesis work at Symetrix. Over a period of several months, The chemical processes were then patented and licensed to several manufacturing companies (Figure 3-22).

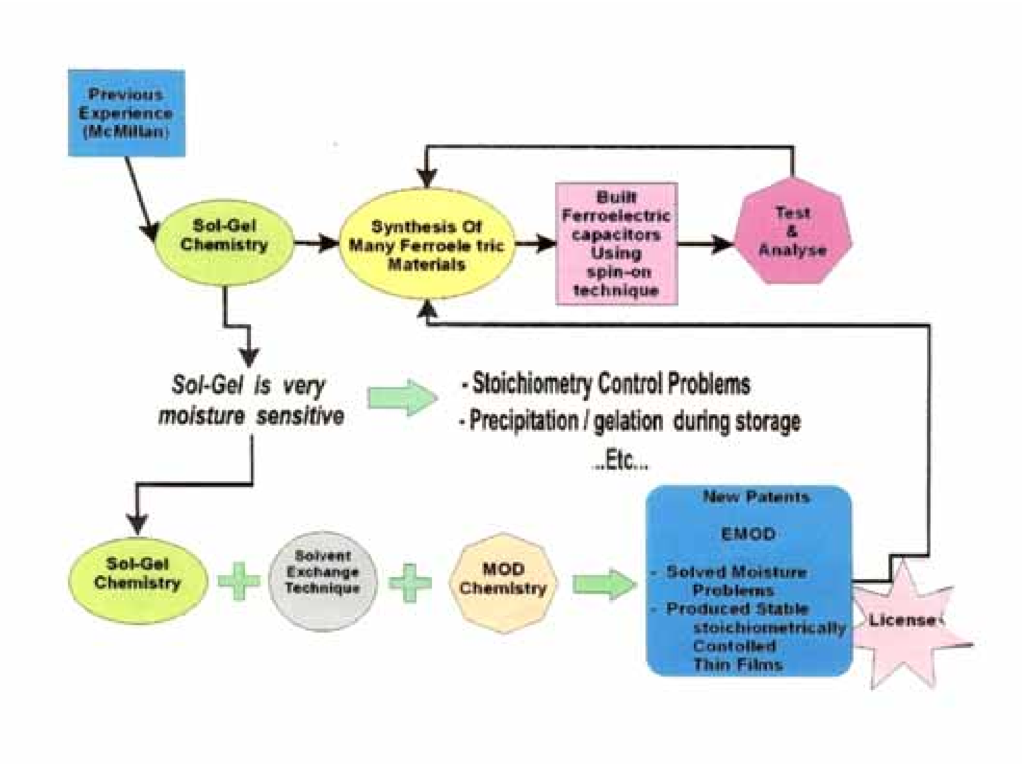


Figure 3-21. EMOD chemical synthesis process development

3.11. LSMCD

Concurrently with development of the EMOD process, Symetrix, with McMillan as Primary Investigator, entered into a SBIR (Small Business Innovative Research) contract with the U.S. Department of Navy to design and build a chemical vapor deposition machine capable of using liquid, rather than gaseous, precursor sources.[42] Up to that point in time, most commercially available chemical vapor deposition machines were limited to single element gaseous precursor sources. Throughout the IC industry, for example, LPCVD (Low Pressure Chemical Vapor Deposition) systems used dichlorosilane and ammonia gases to deposit thin films of Si_3N_4 (silicon nitride) on wafer substrates. These gases were reacted in vacuum, at high temperature, with problematic stoichiometric control.

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[42] McMillan had previous experience from the IC industry in chemical vapor deposition processes and a patent on LPCVD (Low Pressure Chemical Vapor Deposition). Note reference P155) U.S. Patent 4,279,947.

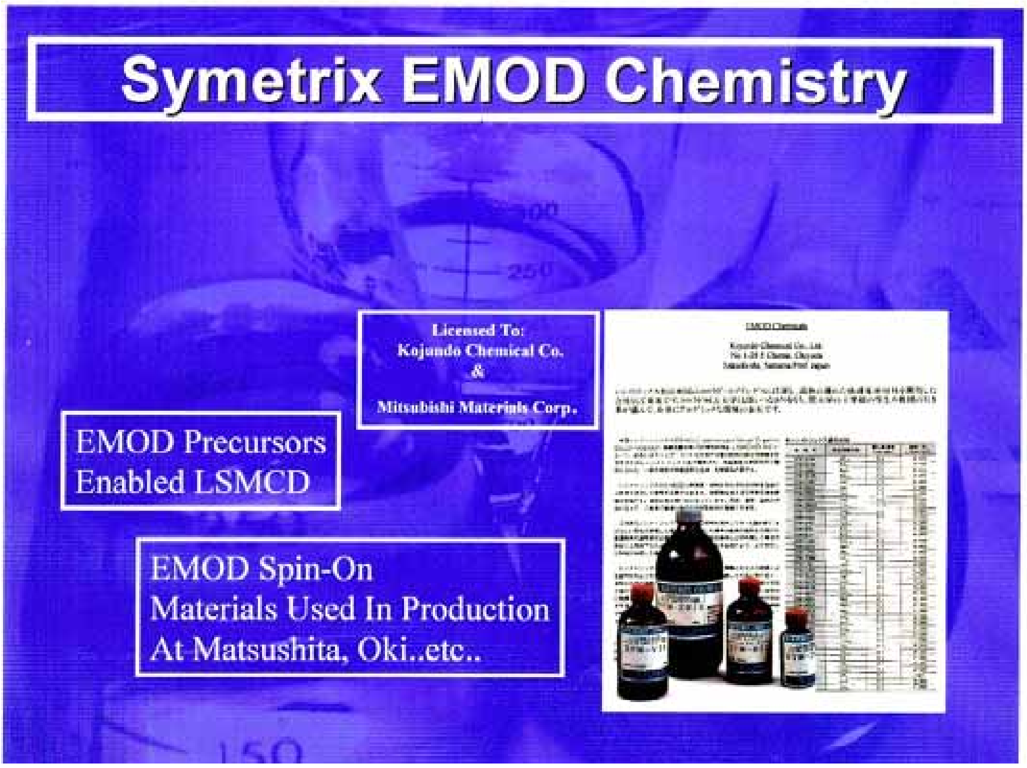

Figure 3-22. EMOD chemistry was licensed to several companies

With separate precursor gases required for each element, this process was limited to deposition of single, or at most three element, compound films. Stoichiometric control of multi-element compounds was nearly impossible.

An experimental vacuum deposition apparatus was designed and built based on the premise that it might be possible to utilize complex compound EMOD liquid sources as CVD precursors. If the EMOD solutions could be processed into small droplets by ultrasonic or other means, then this mist could become the complex compound source for the apparatus. Figure 3-23 shows the R& D strategy and Figure 3-24 shows a basic outline of the operating apparatus used to build several different deposition machines.

The first deposition system built utilized a PZT (lead zirconate titanate) piezoelectric crystal ultrasonic apparatus to generate a mist of various sized

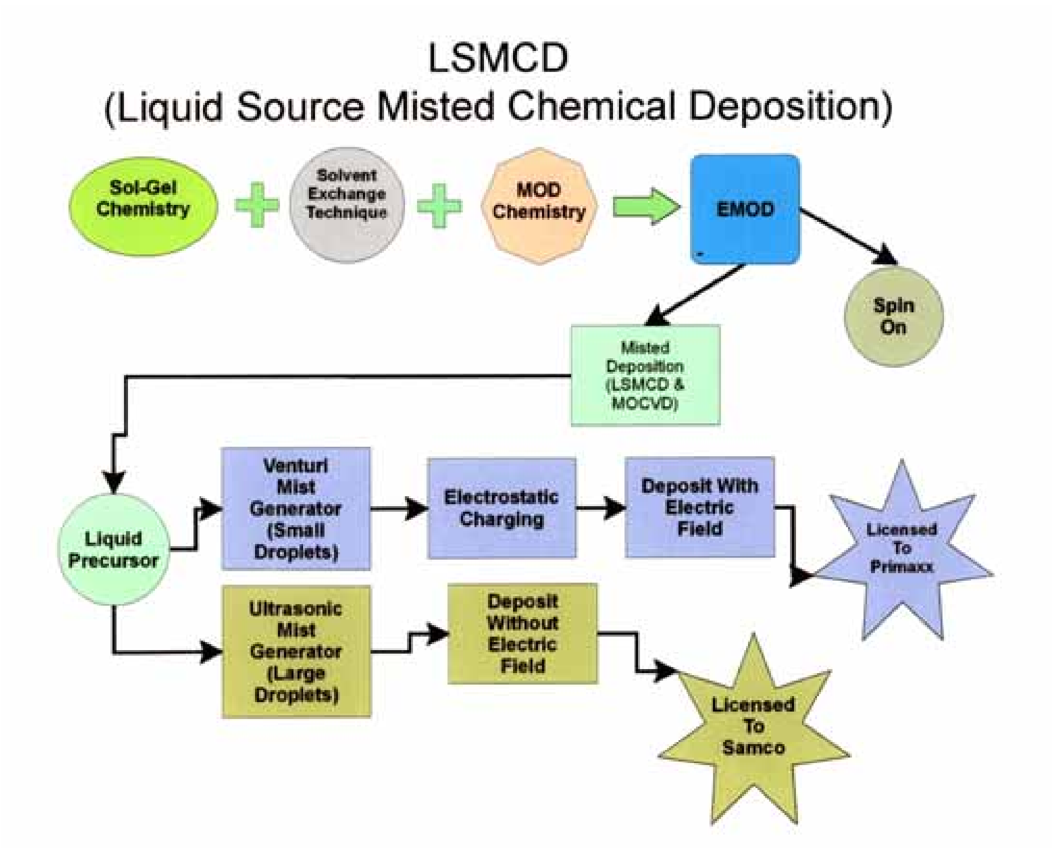

Figure 3-23. LSMCD R&D strategy

particles. These particles were injectred into a vacuum chamber at room temperature and radiated with 240 nm. wavelength ultraviolet light (to resonate hydroxyl ions). The particles "settled" onto the substrates via gravity. Device worthy PZT, BST (barium strontium titanate) and SBT (strontium bismuth tantalate) films were deposited, with fairly good uniformity and excellent stoichiometric control over four inch diameter silicon wafers. McMillan's 1994 LSMCD BST publication in Appendix F discloses initial results.

This technology was licenced to Samco Corporation for the manufacturing of small volume Liquid Source CVD machines to be sold primarily to universities for R & D and materials research (Figure 3-25).

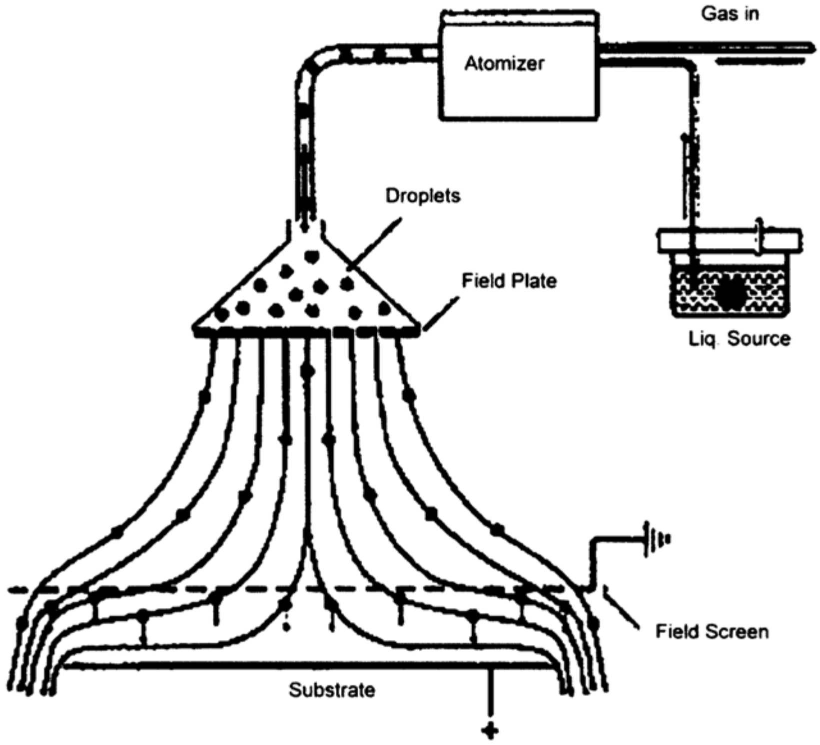

Figure 3-24. LSMCD Experimental Apparatus

The Samco built machine worked quite well for thin film research and development with large feature size (1 or 2 micron) IC structures. For smaller feature sizes, however, the atomizer had to be modified to generate liquid droplets that were very small and uniform in size. It soon became evident that such small droplets would not settle onto the substrates with just the force of gravity. A new prototype machine was built that charged the small particles such that they could be driven to the substrate surface by an electric field. (The charging field plate, the charging screen and ground connections are shown in Figure 3-24.)

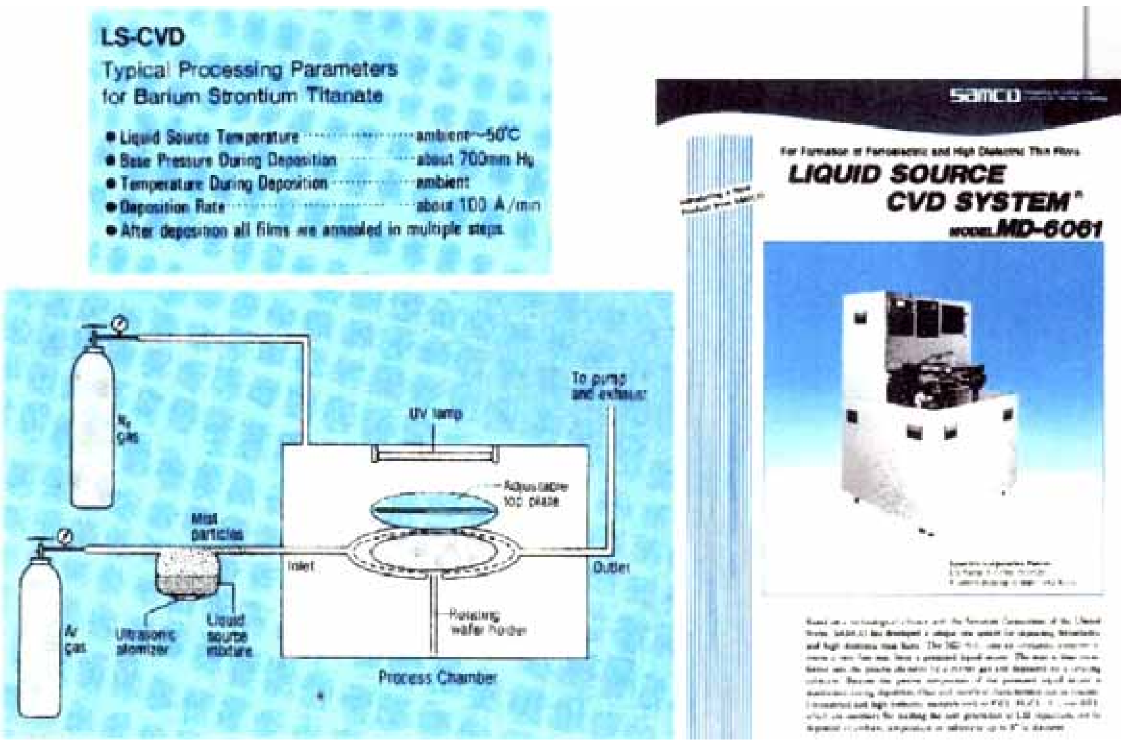

Figure 3-25. Liquid Source Chemical Vapor Deposition technology licensed by Symetrix Corporation to Samco Corporation

Liquid Source Misted Chemical Deposition (LSMCD), the advanced fine particle size technology, was licensed to Primaxx Corporation for manufacturing and sales. Figure 3-26 shows the block schematic for their machine and Figure 3-27 shows the Primaxx production model LSMCD machine being sold (especially in Japan).

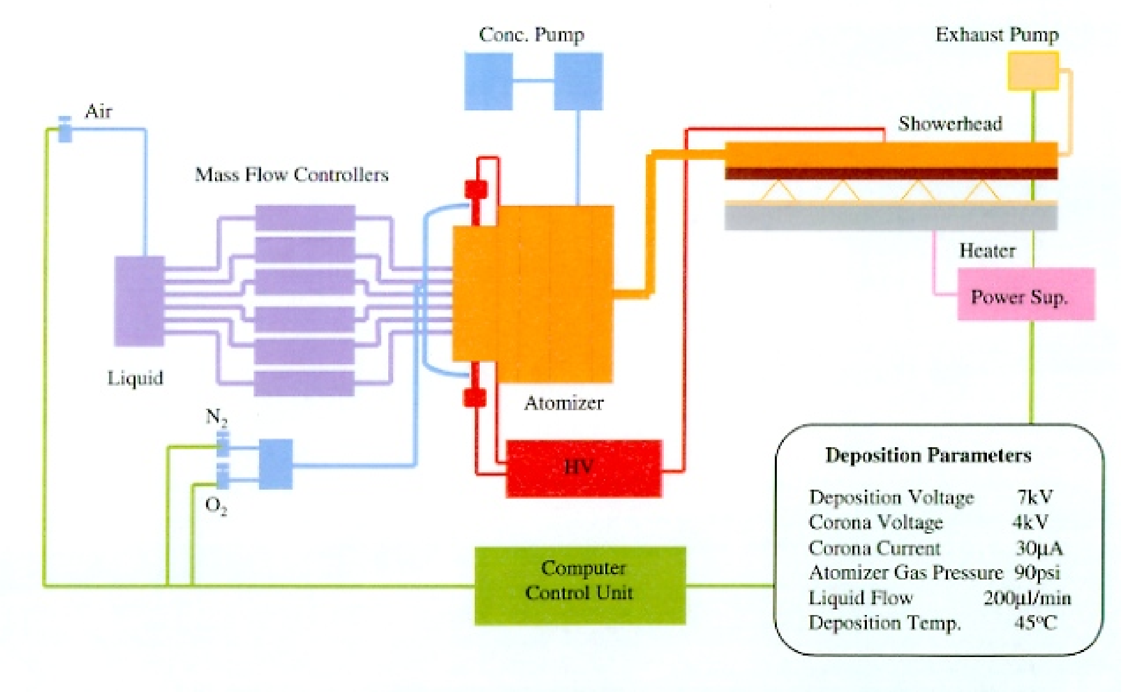

Figure 3-26. Advanced LSMCD block schematic for production machine

3.12. The serendipidous discovery of Y-1

A primary objective of the research was accomplished in 1991 when a number of capacitor structures containing layers of strontium, tantalum and bismuth was accidently over-annealed (Figure 3-28). Normally, such an experiment would have been scrapped, but one of the Symetrix researchers decided, perhaps on a whim, to test the capacitor structures and discovered, to everyone's surprise, that they exhibited superior fatigue-free and retention properties, even when switched to over 10^{13} cycles at 85^{o} C!

Figure 3-27. Production model LSMCD machine licenced by Symetrix Corporation to Primaxx Corp. and manufactured by Primaxx Corp.

This over-annealing mistake had caused the strontium, bismuth and tantalum layers to mix together, resulting in the formation of a layered superlattice material (Figure 3-29). Symetrix was obligated by their US government contract to disclose that a serendipitous discovery had been made; however, they were not required to disclose (to the public) the composition of the new material until it was fully protected by patents. The new material was therefore named Y-1 (not SBT or strontium bismuth tantalate) after the number of the particular process flow outlined in the experimental matrix. (This, of course, was done to prevent infringement of the intellectual property prior to patent filing.)

This serendipitous discovery literally put Symetrix Corporation ahead of all ferroelecctric competition and put them on the map as a world class research group. Y-1, along with the development of extensive device models and new testing methods, opened the way to a number of very significant patents and ultimately to the sale of several new technology licenses.

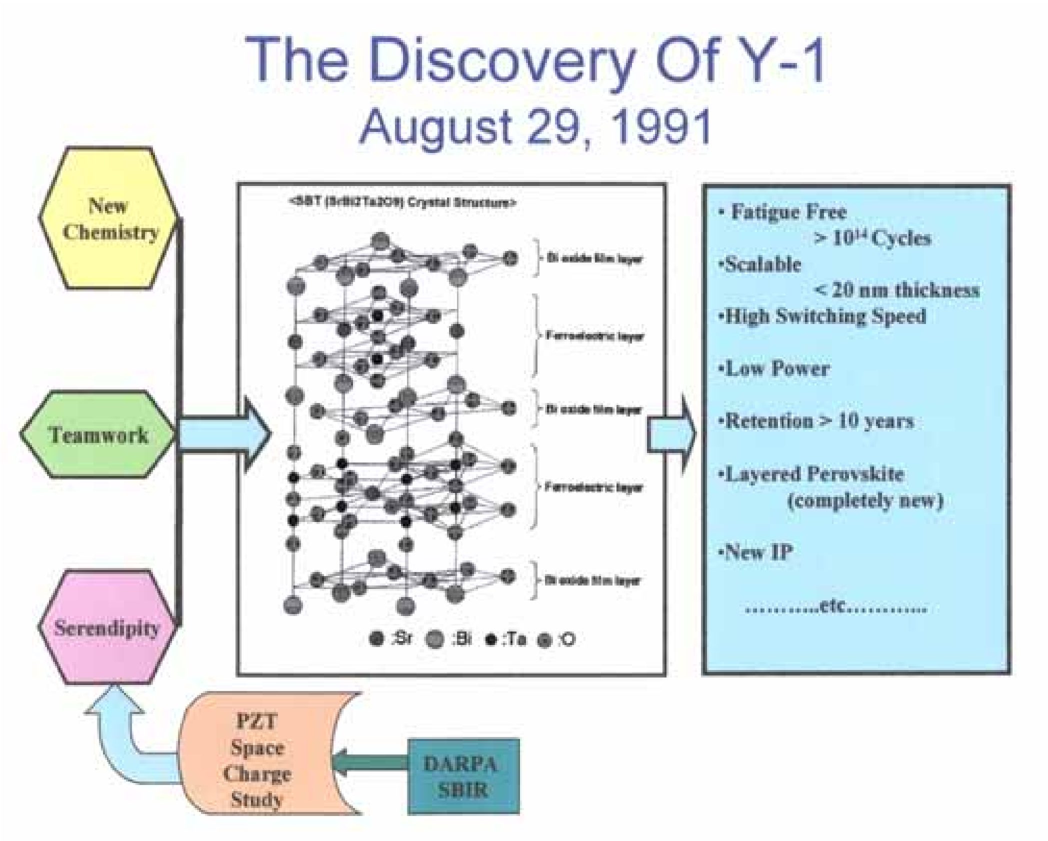

Figure 3-28. The serendipitous discovery of SBT (Y-1). We had found the "Right" Ferroelectric Material!

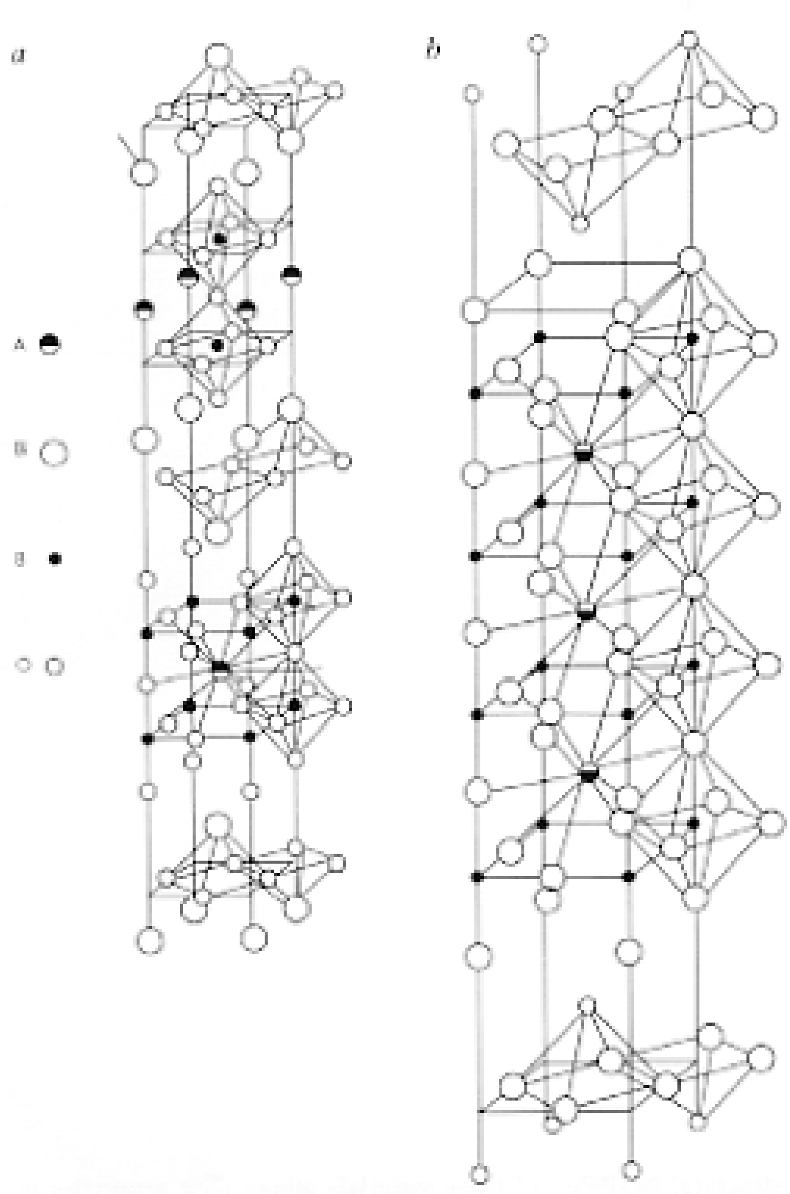

Figure 3-29. a.) The lattice structure of $ABi_2B_20_9$ (where A is a divalent metal such as Sr, Ba, Pb; B is a metal of valence +5, usually Ta or Nb**);** **b.)** The lattice structure of $ABi_2B_40_{15}$ (where A is a divalent metal such as Sr, Ba, Pb; B is a metal of valence +4, usually Ti). (After, Nature, Vol. 374, page 628, April 1995. Paper co-authored by McMillan.)

The initial strategy had worked. Everything that had been strategized many years earlier had now been accomplished. Millions of reliable ferroelectric products are now being sold every year. Following the buyout of two major stockholders, the original partner/founders now own over 70% of the company. The company escaped the venture capital dilution trap and is completely free of debt. R & D contracts continue to be a viable source of revenue and the revenue from royalties is increasing every year.

Chapter 4

Cultural differences that mold international business relationships

4.1. Communication and business between world cultures

The mechanisms enabling global communication are nearly all pervasive. It can be easily assumed that, through the internet and via satellites, communication with people on the other side of the world is as easy as speaking with one's next door neighbors. Such spoken and written communication between people of various cultures must, however, be understood as only the opening dialog for successful commercial exchange. Assuming minimal language barriers and/or the availability of competent translators, there must also be some mutual understanding of, and respect for, the various cultural, social and traditional values separating the parties before effective business transactions can be accomplished. To do otherwise, could lead, at a minimum, to misunderstanding and embarrassment to everyone involved.

Recent statistics indicate that between fifteen and forty percent of US managers sent overseas, fail with their foreign operations and return to the United States much earlier than originally planned [46]. It is the author's opinion, based on some amount of personal experience with companies foreign to the U.S., that many of these failures probably occurred because of insufficient understanding of the cultural, traditional and social differences separating the people trying to do business with each other.

There is a considerable amount of written information available on such differences (reference, for instance, [37], [38], [46], [47], [48], [49], [50], [51]); however, it appears (again, the author's opinion) that completely successful global interactions can only be accomplished between parties actually willing to *participate* in each others cultures. It is far beyond the scope of this thesis to elaborate on the multitude of elements that affect international business relationships; however, the following seems appropriate.

4.2. Classification of cultural characteristics

On a very broad basis, following mostly the works of Hofstede (reference [18], [37], [38], [51]), Ting-Toomey (reference [46]), Anbari (reference [50] and Tung (reference [48], there appears to be a few cultural characteristics that can be categorized and reflected in management style comparisons and business relationships all over the world. Among many other factors, such comparisons generally include: *individualism* versus *collectivism*, *masculinity* versus *femininity*, *long-term* versus *short-term orientation*, *power distance* and *uncertainty avoidance*. Certainly these terms are neither all-pervasive nor all-inclusive, but they do provide some basis for discussion and a means to generally differentiate certain characteristics between different countries. The following definitions and differentiating tendencies did not originate with the author. (In fact, the author has considerable difficulty trying to differentiate between people of different races and cultures.) These definitions and classifications are generally provided, however with some variations, throughout the above references.

Individualism refers to the tendency in a culture for individuals to look after themselves, and put their own needs and goals as a priority ahead of the collective majority. Individualistic countries are reported to include the United States, France, Germany, South Africa and Canada with the U.S. being generally assumed as the highest individualistic country.

Collectivism refers to the tendency in a culture for individuals to work in harmony with other people and other groups, putting harmony and group needs ahead of their individual needs and desires.[43] Collectivist cultures are reported to include Japan, Mexico, Korea and Greece.

[43] It is interesting to note that boisterous, self-centered, ego driven business people and entrepreneurs from the United States are often misunderstood, isolated or ignored in Japan.

Masculinity versus femininity refers to the distribution of emotional roles between genders in a society. In “masculine” societies, people tend to be assertive, tough, and focused on material success. Some masculine societies are reported to include the United States, Japan, Mexico, Hong Kong, Italy and Great Britain.

In “feminine” societies, reported to be present in such countries as Sweden, France, Israel and Denmark, gender roles tend to overlap. In these countries feminine values are said to be prevalent. Both men and women are supposed to be modest, tender, and concerned with the quality of life.

Power distance generally refers to a culture’s expectations regarding how power in an organization is distributed. Different cultures seem to have different expectations regarding power distribution and equality; this leads to how subordinates tend to respond to power and authority. In the high power distance cultures reported to be located in Latin America, France, Spain and most Asian countries, subordinates may tend to show more respect and fear for authority. Authoritative management styles appear to be common in these cultures. In low power distance countries, such as the United States, Britain and much of Europe, subordinates expect to be treated as equals by their bosses. In these cultures, consultative management styles appear to be more effective.

Uncertainty avoidance refers to the level of comfort members of a culture feel in unstructured or unknown situations. Employment stability, rule orientation, and stress over uncontrollable situations are common concerns in such cultures. Uncertainty avoidance is reported to be high in countries such as South Korea, Japan and Latin America. Where uncertainty avoidance is weaker, in countries such as the United States, the Netherlands, Singapore, Great Britain and Hong Kong, people may feel less threatened by unknown situations.

Long-term versus short-term orientation refers to how a culture teaches or programs its members to accept delayed satisfaction or gratification of their emotional, social and material needs. Long-term oriented societies appear to be characterized by persistence and perseverance. People in long-term oriented cultures, such as found in Asia, tend to accept that it may take considerable time to reach their goals and receive gratification. People from countries such as the United States, Canada, Germany Australia and Latin America may tend to be more focused on security and protection of their individual reputations, and hence may expect more immediate results.

Reflecting on all of this, it becomes understandable why business practice, organizational structure, management style and contract understanding varies significantly from country to country and why each country must be studied separately to fully appreciate the interplay between culture and international business issues. It should also be apparent that there cannot possibly be agreement between all people that all, or any, of these cultural classifications are either accurate or relevant. Certainly the universal aspect of such a study is far beyond the scope of this thesis and our attention should logically be narrowed to those areas of the world where the author has some personal experience. McMillan has rather extensive business experience in Japan and Korea and his academic experience at

Kochi University of Technology (especially with the guidance of Professor Keizo Baba) has focused primarily on these areas.

4.3. Business culture: Japan, Korea and the United States

In most world cultures, religion and a long history of family development appear to mold the foundation of its beliefs, traditions and social values. Korean and Japanese corporate cultures, for instance, are influenced to considerable extent by Confucian and Buddhist traditions. Such traditions place emphasis on loyalty to superiors, respect for authority and faithfulness to friends. This results in such practices as lifetime, or long-term, employment, promotions based on seniority, working in collective harmony and family based management systems in these countries. Even with such similarities, however, each country has its own unique management styles and corporate structures.

Japanese and Korean corporate structures are generally based on family-like units. Korean corporations tend to be structured around actual blood (genetic) relatives, whereas Japanese corporations are often built around family-like units consisting of relatives, neighbors, friends, etc.. In both cases, personal connections tie business, family and friends into the same unit. Such connections are not compromised by short-term or bottom-line problems and often last for a lifetime. In both Japan and Korea, it is common for workers to preserve group harmony by sacrificing their individual interests, In Japan, especially, work is considered a meaningful vehicle to prepare employees for participation in social groups and the company is considered to have a legitimate social mission. All of this, of course, is in sharp contrast to the United States and most European countries where law and social norms take precedence over friendship, and employees work only to live while many self-gratifying employers show little interest in social causes or their employee's welfare.[44]

Early in the author’s experience with Japanese companies, he learned that Japan may be quite unique in being a nation where individual identity, to a large extent, is a function of group and corporate membership. Within each Japanese corporation, individuals appeared to have a very strong allegiance to the corporation’s structure, expressing individual submission from below and management benevolence from above.

Such relationships are generally not easily understood and/or accepted by the independent and competitive mentality pervasive in the U.S. and Europe. McMillan soon realized, however, that understanding (and accepting) the philosophy behind such relationships could provide a better understanding of the "inventor's stagnation wall" that he had encountered earlier in the United States. It was really quite simple. If inventors could somehow feel that they were *not* alone, that they were *personally obligated* to work for the common good of society, and that they were happy to share

[44] To Americans, the company is a convenient tool to serve the interests of owners, managers and employees. Americans recognize the company as an organization to generate wealth. They tend to view work as a means to economic end. Employees of the corporation willingly perform work in return for promised compensation.

their wealth, then the stagnation wall might crumble and inventions could then flow into innovations with little resistance. A great solution, but not one that could be implemented easily or immediately!

Early in the history of Symetrix Corporation, contract negotiations with Japanese companies proved to be considerably more complicated than negotiations with American or European companies. Japanese companies tended to emphasize building a mutually trusting relationship prior to entering into any kind of written contract.[45] This, of course, is in stark contrast to the United States, where business deals tend to be structured around suspicion and distrust and where lawyers and legal documents set the tone for the relationship. In Japan, contract terms and subsequent revisions are ultimately effected by committee (almost family-like) action with, usually final and silent, senior management approval.[46, 47]

In the United States, most contracts are negotiated by a few participants exchanging extensive documents laden with "boiler plate" legal language designed to protect and isolate the participating parties.[48] Final

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[45] Without such "trust building" prior to contract negotiations, Symetrix Corporation would never have been able to enter into the JDP contracts that finally broke down some of the stagnation wall referenced earlier.

[46] Collective decision-making in Japan generally involves extensive consultation between all concerned parties until a consensus is achieved.

[47] From personal experience, the author observes that decision making in Korean companies seems to be centered more in top level management than it is in Japan. It appears that the Korean approach to top-down decision making excludes lower level managers.

[48] American workers are not accustomed to being involved in organizational decision-making processes.

signed contracts are usually exchanged (rather impersonally) by mail in the United States, whereas in Japan friendly, and often elaborate, ceremonies initiate new relations with the delivery of the contract documents.

From opening dialog to successful execution of international projects to global commercial enterprises, management on all sides, and at all levels, must recognize and appreciate the significance and pervasiveness of cultural diversity. The world has moved far beyond the point where isolationism can play a role in business strategy. Any new business model must anticipate multi-cultural communication at all organizational levels and must promote flexible leadership capable of inspiring cooperation, creativity and innovation across international boundaries.

Chapter 5

Strategies for sustainability and business growth

5.1. The single technology model

Most business startups begin with the presentation of a business plan to groups of potential investors, bankers, venture capital groups or other wealthy individuals. Such investors, whether ethical or not, will access the investmen risk factors and structure *their* interest, service and expected ROI (return on investment) rates accordingly.[49] This means, of course, that most companies start off with a significant debt load and the risk of losing everything (to the investors) if sufficient revenue (investor ROI) is not achieved in a short period of time.

Assuming success, at some point in time (usually after several years) there must be a break-even point where the company shows a profit and a growth ("S") curve can be generated.[50] As discussed below in Chapter 7,

[49] It must be noted that the author has had several unpleasant experiences with venture capital firms attempting to control intellectual assets and corporate management positions in exchange for minimal investments.

[50] The author is grateful for the considerable insight into S curves provided by Professor Osamu Tomisawa of Kochi University of Technology.

both investors and corporate founders must also, at some time, exercise exit strategies that maximize return on investments.

A simple financial model for such a classic *single* technology business is shown in Figure 5-1. It is obvious that exit point determination (especially for the founders) is not a simple process with this model. In most cases, outside investors will structure their agreements in such a way that they insure maximum financial success far ahead of the founders. It is quite common, at least in the United States, for investors, especially venture capitalists, to take over early management of the fledgling company and terminate the founders within a year or so of startup. Failure rates are quite high for startups following this single technology model and it appears that some of the business practices associated with it are quite detrimental to technical progress and economic growth.

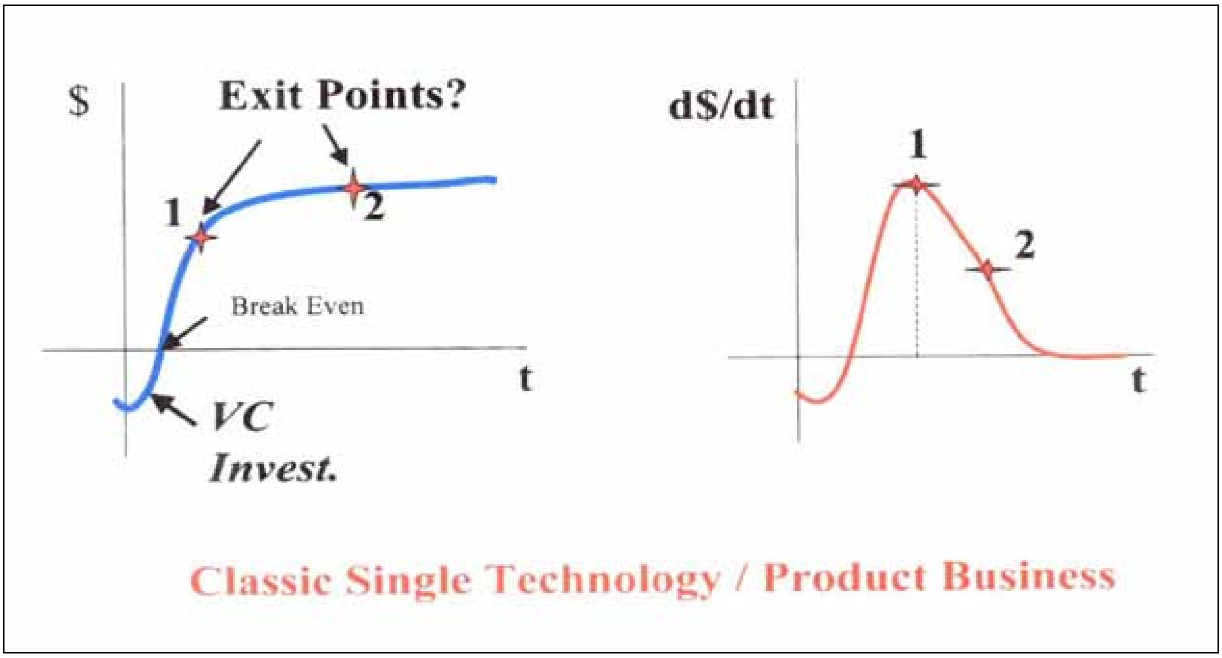

Figure 5-1. Common Single Technology Business Model

5.2. The multi-modal model

Following the line of reasoning developed by Christensen, Foster and others, the multi-modal IP model shown in Figure 5-2 alleviates many of the risk factors associated with the classic model [42], [43]. Symetrix started with this multi-modal business model and has successfully used it for nearly twenty years.

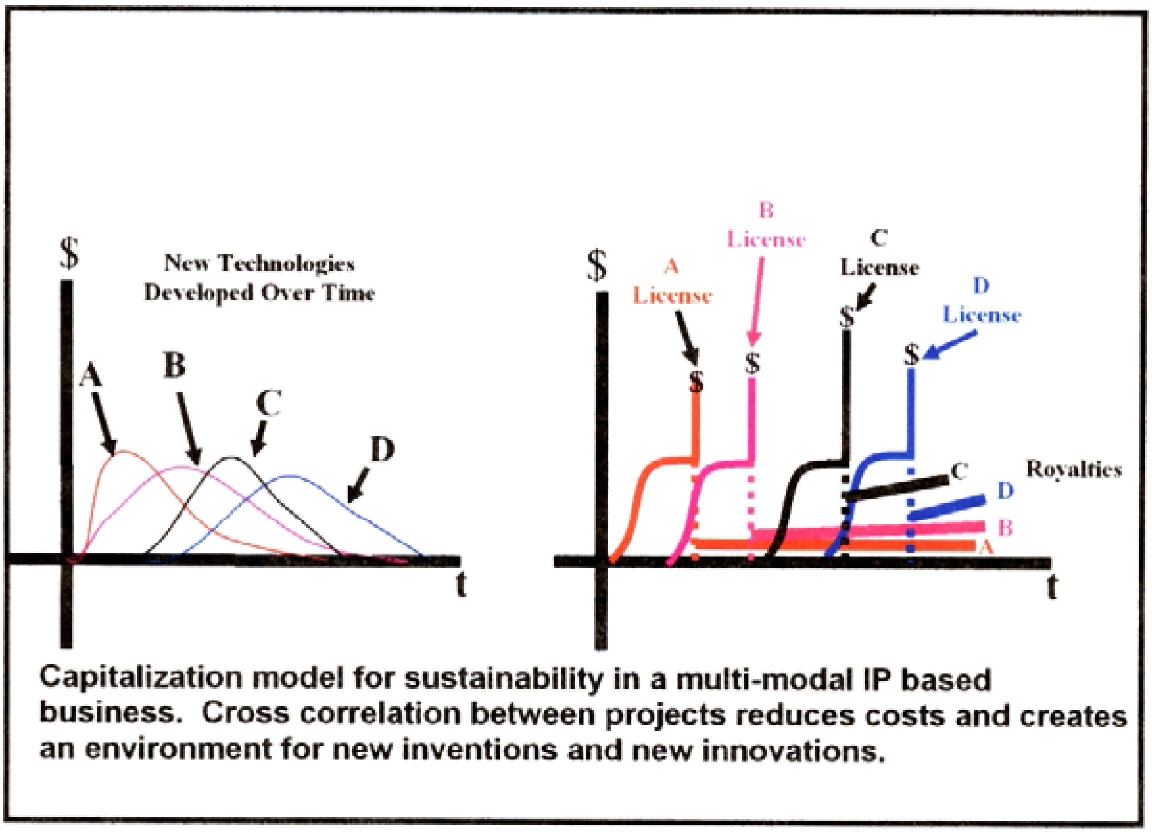

Figure 5-2. Multi-modal IP based business model

As described in Chapter 6 above, the founders of Symetrix Corporation (Araujo and McMillan) did not seek initial funding from any lending or investment source. The startup was funded through proceeds from SBIR contracts, hence no initial debt was incurred. Rather than focusing on a single technology path, several projects (chemicals, machines, devices, models, etc.) were run in parallel, with their individual maturing S-curves sequentially overlapping. Rather than trying to exit any single technology at some prescribed time, each technology was licensed at maturity to other companies with resulting license fees and royalty streams returning to Symetrix. As these royalties and license fees were added to corporate reserves these funds were also used to develop and leverage new technology (in a cost effective manner), thereby establishing sustainability and corporate growth.

5.3. A self-correcting neural network model

Looking back at our experiences over the last twenty years, it appears that, somehow, all of this could be modeled with a Self-Correcting Neural Network. Figure 5-3 shows the author's initial attempt at such a model.

In this configuration, the inputs x_1, x_2, x_3,.... etc.... represent income (with respect to time) from JDP's, royalties, etc., and x_4 represents expenses or negative income. These quantities, times their weight factors w_1, w_2, w_3..., are summed with the minimum of such total (over any particular time period) adjusted by the desired profit and reserves, d(t), such that e(t) equals y(t) the output. If the output is running profit then nothing is done to effect the weights, w_1, w_2, w_3,... etc., and the system runs freely. If, however, the profit is unsatisfactory, then the function f(t) is less than some set amount and a switch is closed causing the weights (adjustment factors) to be regulated. The network should then recycle and readjust the various parameters until the desired output is achieved.

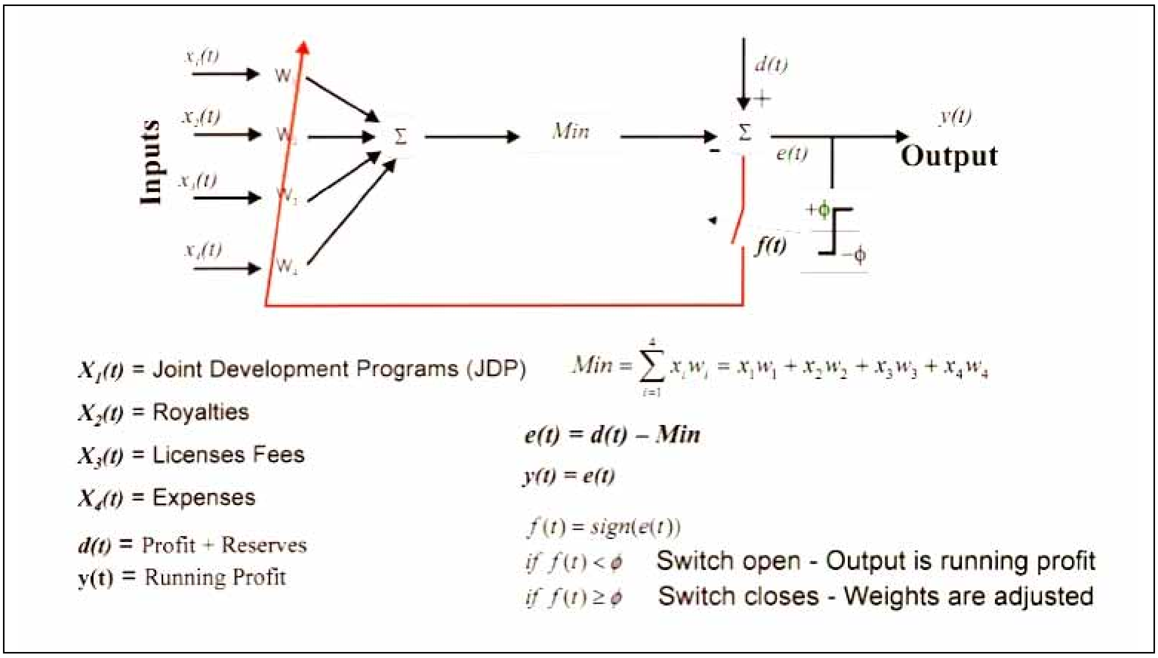

Figure 5-3. McMillan's initial attempt at using a neural network to model sustainability

In principle, this model should work quite well. With the ongoing advances being made in global computer networks and communication systems, and with the availability of massive amounts of non volatile, fast, FeRAM memory, this model could become reality in the very near future.

Chapter 6

Protecting intellectual property through business relationships and managing the cost of patent protection

6.1. The patent assessment

Like most living organisms, a company begins to die as soon as it stops growing. (This becomes evident with consideration of the single technology S curve associated with the model in Figure 5-2.) Symetrix Corporation continues to grow after nearly twenty years because it has leveraged its intellectual capital in a rather ingenious way. Through alliances with a few large corporations, Symetrix has been able to minimize its own bureaucratic structure by reducing the number of employees, along with the associated burden and overhead rates, while continuing to generate new patents and avoid the difficulties and obligations associated with outside investment.

As discussed earlier in Chapter 2, the path from invention to commercial realization can be perilous and very expensive. With any invention, the inventor must determine the initial disclosure path early in the process. In some cases the invention might best be kept secret. This is especially true if the invention involves processes, ingredients or techniques that cannot be reverse-engineered. (Coca-cola and Smith's cough-drops are examples of such inventions.)

In most cases, however, inventors should try to get patents on their achievements prior to any kind of business negotiations.[51] Without a patent, the inventor has little recourse to infringement or intellectual property theft. Inventions that are not patented generally bring very little financial gain to the inventor.

Patent costs can be staggering. It is not unusual for the inventor, or the inventor's financial backers, to spend many thousands of dollars trying to get viable patent coverage. Even after patents are issued, there are significant costs associated with maintenence and other fees in every country where the patent has recognition. (In the case of Symetrix Corporation, with over 150 issued patents, this also amounts to many thousands of dollars every year.)

[51] It should be noted that there are several vehicles for conferring intellectual property rights, such as material transfer agreements, licenses, technology transfer agreements, research agreements, joint development agreements, etc.[52].

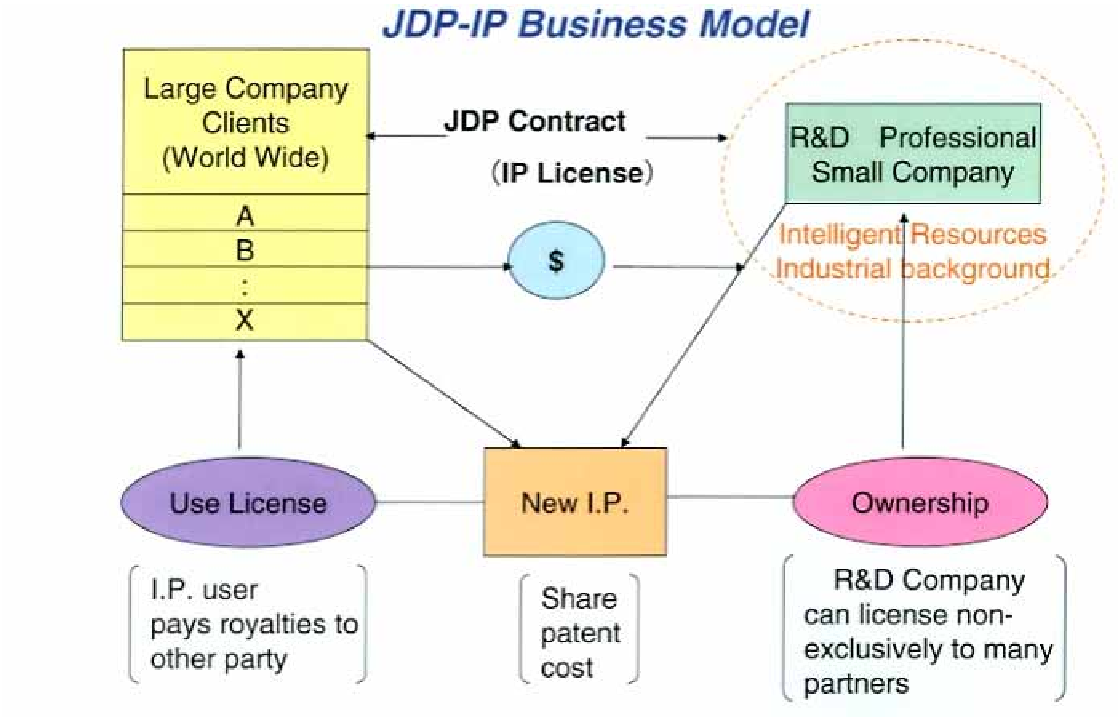

Figure 6-1. Joint development program with IP/Patent protection.

6.2. The JDP patent protection model

Early in the development of Symetrix Corporation it became evident that the multi-modal model (shown in Figure 5-2), with its technology licensing features, could only work if Symetrix entered into joint development programs (JDP's) with other companies. This resulted in the model shown in Figure 6-1 and ultimately in the sale of technology licenses to a number of companies including Panasonic, Mitsubishi, Raytheon, Primaxx, Kojundo and many others.

The model is quite simple. Company X enters into a JDP with company Y such that company X pays company Y to manage and originate the joint R & D activities. The results of their joint efforts are patented with both parties sharing the patent costs and both parties receiving patent assignment. A non-exclusive license to patent use is granted to both parties with royalties being paid by either product producing party to the other party. Company X and company Y can both license (non-exclusively) to other companies with the approval of their joint development partner. The model works extremely well. Patent filing and maintenence costs are shared equally by the JDP partners, effectively cutting the cost in half for each of them.

Patent costs, of course, are only part of the problem. Once a patent is issued there are no guarantees that someone, somewhere, will not commit patent infringement, fraud or otherwise try to steal the intellectual property. With globalization of the economy, policing and protecting intellectual property has now moved from being a local concern to becoming a complicated international legal involvement.[52] Laws affecting intellectual property not only vary from country to country, but the level of IP protection varies considerably from country to country as well. In many cases, it is unclear which courts have, or will have, jurisdiction over disputes relating to intellectual property infringement violations.[53] In general, however, such problems must ultimately be resolved in the country of

[52] International laws and legal jurisdiction concerns are likewise applicable to trade secrets, copyrights, brands, designs and trademarks.

[53] Some countries/cultures restrict or question private property versus public common good and copying is still considered flattery in some areas of the world [52].

infringement. For an (international) intellectual property lawsuit to succeed, the defendant generally must reside in the country in which the lawsuit is filed Clearly, prejudice and judgement enforcement issues are often insurrmountable [52].

Our model doesn't necessarily solve such international IP conflicts; it does, however, simplify patent enforcement problems by placing the defendents and complainants in the same country under the same judicial system. This is obvious by the fact that the international partners in the JDP are not only owners but strong patent defenders *in their own countries* as well.

There can be little doubt that globalization is out-pacing our capability to manage and protect intellectual property. New markets are opening up in countries that, until recently, had little regard for intellectual or private property rights. In such countries, international trade and intellectual property treaties are slow to take effect, yet the international exchange of goods and services (especially via the internet) continues to accelerate.[54, 55]

There are obviously no quick or easy answers to the problems associated with intellectual property generation and protection, especially on a global scale. The model presented in this chapter, however, may alleviate

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[54] Product life cycles in many industries are shortening. The length of time and the amount of investment required to obtain intellectual property rights (especially patents) can be disproportionate to the life of the products [52].

[55] It is interesting to note that some governments view WTO (World Trade Organization) rules as a starting point for negotiations rather than a set of binding regulations [52].

some of the more difficult problems facing start-ups, small businesses and even large corporations as they attempt to deal across international borders. It seems obvious that the recognition and rewards associated with ownership of inventions and creative works should stimulate further inventive and creative activities which, in turn, should stimulate economic growth for all parties involved. Anything short of that must be considered unsatisfactory.

Chapter 7

Evolution of the new corporation

7.1. The changing business environment

The Symetrix business model referenced above has been proven successful. After nearly twenty years of operation, the company is debt free and probably has sufficient reserves to continue pursuing new technology and expanding its influence in the global marketplace. The problem, however, is that no one can predict exactly what the future will bring, and the rapidly changing global business environment could force our model into obsolescence.[56, 57]

Peter Drucker stated in his book, *Managing In The Next Society* (Drucker, page 3, reference [56]):

> "*It is something that practically no one foresaw or, indeed, even talked about ten or fifteen years ago: e-commerce – that is, the explosive emergence of the Internet as a major, perhaps eventually*

[56] It is commonly believed (U.S. folk-lore) that Yogi Berra once said, "The future ain't what it used to be!"

[57] Global business is defined by Griffin as, "A business that transcends national boundaries and is not committed to a single home country." (Ricky Griffin, *Management*, page 133, reference [61].)

the major, worldwide distribution channel for goods, for services, and, surprisingly, for managerial and professional jobs."

From a business perspective, the mechanisms for inexpensive global communication are already in place. Competition has now moved from local influence to, in some cases, global jeopardy. Because of the computer, the internet and extensive satellite communication systems, every business, large or small, must now compete in the global market. As Moore states in *Crossing The Chasm* (page 182, reference [45]:

> *"....As a future channel of distribution, the Internet represents the most significant change in computing to date, and maybe ever. It promises to reingineer all other forms of commerce, not eliminating them, nor even disintermediating them, but simply reconstructing them to incorporate its phenomenal reach and service capabilities...."*

With continually improving air and surface transportaton systems, larger cargotainer shipping facilities and global propagation of a few common languages, new labor and material sources are becoming available to nearly every business on the planet. In other words, the *supply chain* for most businesses has changed, and is continuing to change on a regular basis.[58] Many high cost local operations can now be shifted to specialized

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[58] Armstrong and Kotler, in *Marketing, An Introduction*, differentiate marketing channels

facilities (and experts) around the world. For instance, a specialized central IC fab located in a low labor cost region of the world, can now service several competing fabless semiconductor companies (located in other parts of the world) such that everyone along the supply/value chain recognizes profit.[59]

7.2. Evolving business philosophy and strategy

It seems obvious that traditional business philosophy will require some modifications. Where traditionally, companies were inward-looking for self optimization they now must become globally cognizant of supply and value chain optimization. Corporate organization structures must change from common *independent* stand-alone configurations, such as matrix, horizontal, mixed or vertical, to *interdependent* entities cooperating closely on a global scale. As Drucker stated in *Management Challenges for the 21st Century* (page 61, reference [27]):

> *All institutions have to make global competitiveness a strategic goal. No institution, whether a business, a university or a*

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from supply chain as "Marketing channels consist of distributors, retailers, and others who connect the company to its buyers. The supply chain describes a longer channel, stretching from raw materials to components to final products that are carried to final buyers." (Armstron and Kottler, page 22, reference [41].)

[59] Variously defined, a *value chain* is a string of suppliers, companies or workers that cooperate (work closely together) to satisfy market demands for a particular product.

hospital, can hope to survive, let alone to succeed, unless it measures up to the standards set by the leaders in its field, anyplace in the world."

Where traditional stand-alone companies shared minimal information with other companies, they may now be forced to share extensive information with all other parties on their supply and value chains.

Independent companies oriented toward specific commodities or devices may now be forced to direct their efforts towards differentiated products or systems that incorporate original devices into larger systems more closely aligned with direct consumers. It seems obvious that single component producers, especially if they are a relatively small company, cannot survive if they do not integrate their work products with system integrators. (Note the example of Symetrix Corporation working closely with Panasonic Corporation to incorporate the ferroelectric memory into smart card, identification, communication, and other systems.)

On the marketing front, the focus must shift from cost and price to value and quality. (Remember that anyone in the world can now use the internet to educate themselves and search for the best price and best quality any where else in the world.) It is the author's opinion that, in this new global market, value and quality will ultimately win against cost and price every time! In like manner, we easily see that suppliers will no longer be able to simply push onto (force sale to) their customers whatever they have available. Instead, the seller-buyer power relationship must now shift more closely to satisfy exactly what the customer needs or wants. As Moore said in *Crossing The Chasm* (page 189, reference [45]):

> *".....All organizations are market-driven, whether they acknowledge it or not. The chasm phenomenon-the rapid acceleration in market development followed by a dramatic lull, occurring whenever a discontinuous innovation is introduced drives all emerging high-tech enterprises to a point of crisis where they must leave the relative safety of their established early market and go out in search of a new home in the mainstream. These forces are inexorable-they will drive the company. The key question is whether the management can become aware of the changes in time to leverage the opportunities such awareness confers.*

How all this affects business strategy seems quite obvious. The new corporation must compete in new and evolving markets around the world. Local markets may easily be over-run with foreign goods. Inernational laws and treaties will continue to offer ineffective and insufficient defense against global piracy and counterfeiting. Many companies will continue to decentralize their operations, with production, marketing and R & D moving to lower cost areas of the world. The internet will be utilized to satisfy most communication needs and local operations will minimize labor, burden and overhead costs by reducing the number of employees and utilizing specialized, experienced consultants and part-time workers.

In view of all this, the growth and evolution of the new world-spanning corporation is obviously going to be dependent on many of the factors above outlined. No longer can any company, including Symetrix, continue to operate in the new globally competitive business environment, with a philosophy that worked twenty, or even ten, years ago.

7.3. Value building, exit strategies and longer life spans

With a few variations caused by cultural or other biases, retirement plans are becoming world pervasive, yet apparently increasingly ineffective. Even in countries where families still take care of their elderly, such as in Japan, Korea and China, increased life span considerations are driving every worker to re-evaluate his/her own long term financial security. In the United States, where social security has become a political issue, thousands of young workers are being told that, even if they pay into the government sponsored social security program for most of their lives, there will still be insufficient funds available for them to retire with dignity. Is it possible that there is really something wrong with the whole philosophy behind long term security, value building and retirement?

It is commonly believed that, prior to entering into any kind of business relationship, the inventor, innovator or entrepreneur should try to plan ahead to maximize their own (personal) return on investiment (ROI). It seems that the whole idea behind writing a business plan is to maximize the corporate founders personal ROI as well as the investors. Unfortunately, it seems that during the writing of a business plan, most people fail to address the long term issues, such as corporate continuity and exit strategies.

There are many ways that exit strategis have been, and might be, defined. Logically, part of any definition, however, should probably start with the simple premise that at some point in time, every business owner leaves his/her business, voluntarily or otherwise. Some people, of course, may be very reluctant to think about such things, but even those people want to maximize their income to accomplish personal, financial, income, estate planning and other objectives. Unfortunately, many business owners, even those who are not afraid to die, become so busy worrying about, and running, their business that they fail to take into account that one day they will exit.

Every situation is as unique as the personality of each person, so each situation must be addressed in a way that is taylored to the individual. The result of such consideration, however, must arrive at the fact that everyone becomes incapabale of, or disinterested in, working at some point in time. In the end, every business, large or small, will probably change hands. Ownership, and certainly management, will change either by IPO (Initial Public Offering), sale, transfer to a family member or by merging with another company.[60]

It appears that the most common exit strategy today may be the acquisition of the start-up by a larger corporation. Michael Baird, in *Engineering your start-up* (page 139, reference [60]) states: ".....*More and more entrepreneurs are including a section in their business plan that recommends a preferred exit strategy: for example,*

[60] It should be noted that relatively few start-up companies ever make it to an IPO.

acquisition by a large company that is also a strategic partner. This is a change from a few years earlier when few gave thought to whether (and if so, how) the business would be sold. The reason for this new awareness is probably that more start-up entrepreneurs see starting a business as a means to an end, not an end in its own right…."

In his book, *Managing In The Next Society*, (page 249, reference [56]), Drucker says:

> *"……In the past, employing organizations have outlived employees. In (the) future, employees, and especially knowledge workers, will increasingly outlive even successful organizations. Few businesses, or even government agencies or programs, last for more than thirty years. Historically, the working life span of most employees has been less than thirty years because most manual workers simply wore out. But knowledge workers who enter the labor force in their twenties are likely to be still in good physical and mental shape fifty years later.*

So it appears that, regardless of what is planned for exit strategy or retirement, future knowledge workers, and that might include nearly every person on the planet, will probably outlive their company and, consequently, their retirement savings. The question then becomes, "why should anyone bother with such plans in the first place?"

Drucker goes on to say (pages 249-250, reference [56]):

"…Increasingly, employees take early retirement as soon as their pension and social security rights are guaranteed for the time when they reach traditional retirement age; but they do not stop working. Instead, their "second career" often takes an unconventional form. They may work freelance (and often forget to tell the taxman about their work, thus boosting their net income) or part-time or as "temporaries" or for an outsourcing contractor or as contractors themselves. Such "early retirement to keep on working" is particularly common among knowledge workers, who are still a minority among people now reaching fifty or fifty-five, but will become the largest single group of older people in America from about 2030."

Who knows better about this than Peter Drucker. At the time of this writing he is nearly 100 years old and still working every day. From the author's perspective, value building and exit strategizing may become obsolete philosophical discussions in the near future.[61] Both concepts appear to be contingent on short life spans, health problems and fear of senility with old age. Perhaps future generations of knowledge workers will consider work as essential, enjoyable and an integral part of their lives. Then, perhaps people around the world and will stop thinking about continuous saving, value building and retirement plans all together and begin living every day as if it were their last.

[61] It might be noted that the author is 69 years old as of this writing, and fully intends to continue working until he expires.

Chapter 8

Conclusions

Using the evolving FeRAM as a case study, we have explored some fundamental aspects of inventors, innovators, entrepreneurs, dreamers, etc., especially as they relate to the author. This study has also shown how a company can be started with minimal physical assets and yet sustain operations for nearly twenty years without the infusion of borrowed money or venture capital. It is interesting to note that, even with the circumstances of this particular case, including minimal funding, public disbelief, antagonism of competitors, and many other problems, the technology still evolved on a time scale exactly corresponding to that predicted by Simon Sze [19].

Symetrix Corporation, the primary focus of this study, is still prosperous after nearly twenty years of operation. The company has borrowed no money, it escaped the venture capital dilution trap (a major concern of the founders), and it remains completely free of debt. Following a recent buyout of two major stockholders, the original partner/founders now own over 80% of the company. R & D contracts continue to be a viable source of revenue and the revenue from royalties is increasing every year.

The maturing rate for layered perovskite SBT FeRAM devices during the last few years has been astonishing. Symetrix' main licensee, Panasonic, began shipping FeRAM based contactless identification (ID) cards in 1998. In that year they shipped 12 million cards and in 2001 their sales grew to 150 million pieces (Figure 8-1). Panasonic has also been shipping mixed signal FeRAM ASICS, at the 0.8/0.6 micron double level metal technology level , at a rate of 2-3 million units per month for the last few years. Now it is shipping 3 and 4 level metal 0.18 micron ferroelectric embedded mixed signal microcontrollers at several million units per year. In May of 2005, Matsushita/Panasonic announced that they had sold, to that date, 100 million FeRAM chips!

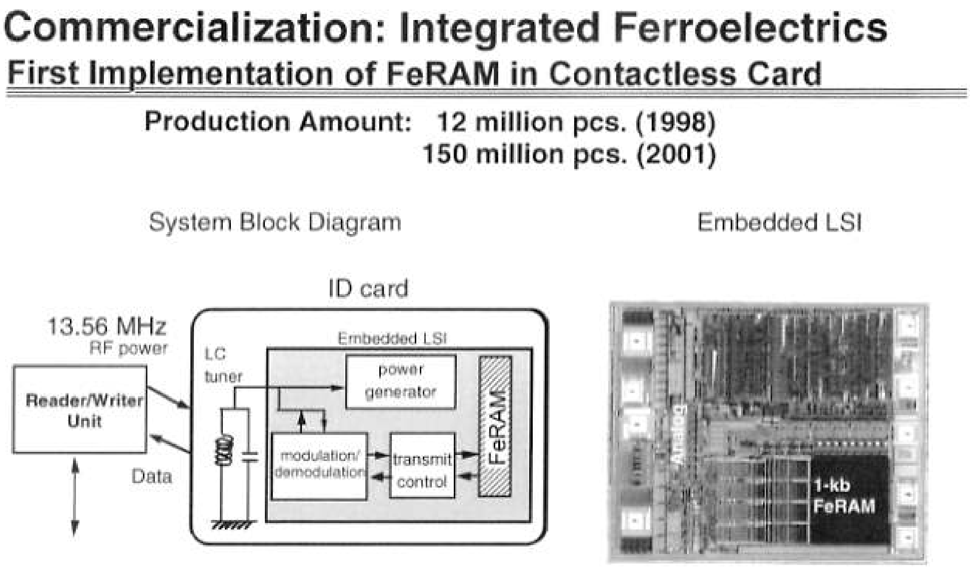

Figure 8-1. Panasonic integrated ferroelectric contactless cards (figure courtesy of Matsushita Corporation)

In the non-switching (non-memory) area, Panasonic has shipped over 600 million units of BST (high dielectric constant) GaAs MMICS since 1993. This technology, which enabled the miniaturization of mobile phones in

Japan, was co-developed by Symetrix Corporation and Matsushita during the early 1990s. (For McMillan's contribution to this effort, refer to his 1994 paper, *Deposition of barium strontium titanate and strontium titanate via liquid source chemical vapor deposition*, in Appendix F.)

No one, of course, can really predict the future; however, it appears that Matsushita's world FeRAM market forcast from a few years ago may be accurate to a variance of less than three years (Figure 8-2). If this is, indeed the case, then the FeRAM story could possibly go down in history as an achievement in league with transistors and integrated circuits.

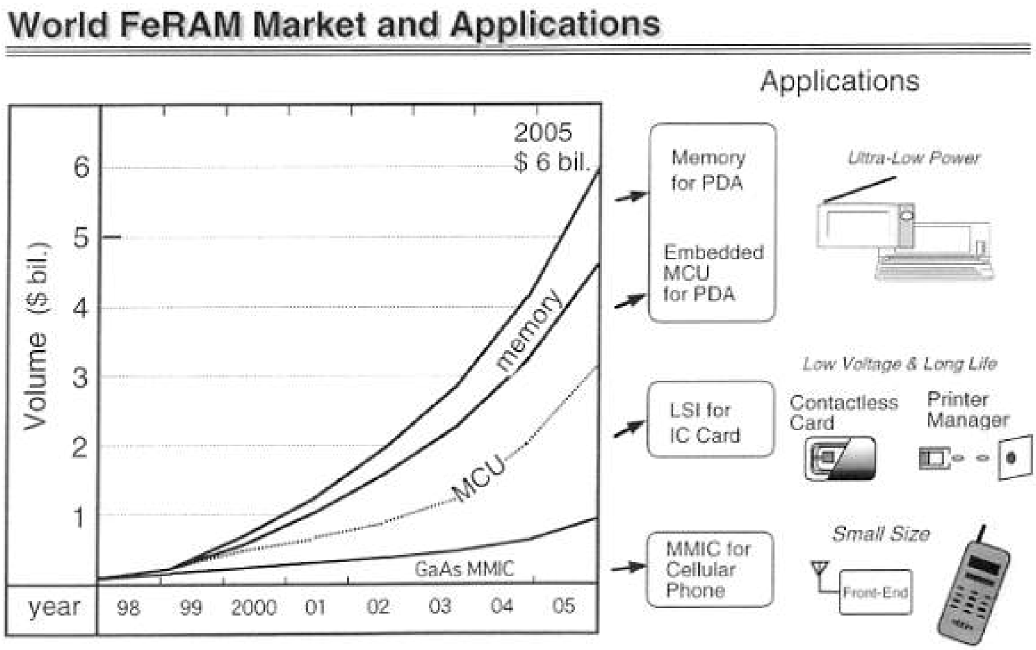

Figure 8-2. The rapidly expanding market for ferroelectric devices (figure courtesy of Matsushita Corporation)

Reflecting back to McMillan’s dream of “cubic integration” in the early 1970s, it appears that his ideas are as valid today as they were thirty years ago. The semiconductor industry is still chasing ever smaller feature sizes and still trying to pack more and more components into smaller and smaller spaces. Moore’s Law aside, it seems more relevant and logical today than ever before, that the exceptional ideas of Edmond Abbott, who lived in the 1800s, long before integrated circuits were even thought of, should be examined closely. It is easy to imagine Abbott's "Flatland" as the two dimensional geometry of planar circuits and McMillan’s "cubic integration" as the coming into awareness of three dimensional integrated device structures [20].

In Chapter 1, the author stated that: "…He was unaware that some of his efforts might possibly result in breakthroughs that would have significant and positive effects on global society.".....and, that "This thesis represents part of the author’s awakening to those possibilities and his struggle to achieve that understanding...."

After thirty years of searching, the author now realizes that, in many respects, this experience, this awakening, has become not only an education, but something philosophical, perhaps even something spiritual, as well. In the book, "The Mind of Management," by Masaharu Matsushita, Konosuke Matsushita is quoted as saying (pages 20 -21, reference [62]):

> *"Even after returning home, I could not get the thought of religion on the one hand and management on the other off my mind. I stayed awake for a long time thinking about it.*

Religion was a holy pursuit aimed at guiding people out of suffering and toward happiness and peace of mind. Our business, too, is sacred, 1 thought, in the sense that industry provides necessities that sustain and improve man's existence. Indeed, the ultimate aim of production is to wipe out poverty and create prosperity. There is an old saying in Japanese that poverty is harder to bear than a thousand illnesses. Eliminating poverty is a sacred task, the loftiest purpose in life. To achieve it we must work hard and produce a great abundance of goods; this is our mission and our enterprise. Production aimed at enriching the life of every person on earth is the sacred mission of a manufacturer. Not only spiritual peace but material abundance is necessary if the quality of human life is to be better and people are to be happier. You may be spiritually enlightened, but if you are deprived of certain material comforts you will find it hard to survive. And of course, the greatest abundance of material wealth is worthless unless you enjoy fulfillment and a purpose in living. Spiritual peace and material abundance are as inseparable as the two wheels of a cart. So, I realized, management of a religious organization and of a business concern are equally sacred and necessary pursuits."

To the mind of the author, Konosuke had put into words, what McMillan had believed all along, but had been unable to express.

It appears now that we have looked into the future and concluded that the adventure is just beginning.

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APPENDICES

A. The First Ferroelectric Memory IC

McMillan Disclosure to Motorola, February 7, 1976

From: Larry McMillan
Mail Drop:
Phone:

Date: February 7, 1976

To: Curt Foster
Keith Bane
Bob Jenkins
George Averkiou
Bill Martino

Subject: Ferroelectric Memory IC
Processing Notes
Technovation $^{III}KNO_3$

The attached notes briefly outline a processing sequence that may be used to produce large array ferroelectric memory IC chips. Other than the Technovation method for deposition of $^{III}KNO_3$, the processing steps should not entail techniques foreign to Motorola.

The advantages of this type of memory are fairly obvious.

1. Very large array RAMS (64K and greater) should be possible with this technology. The memory function does not depend upon silicon so the whole chip may be used for address and decoding circuitry and the memory cells placed on top of the chip.

2. The memory is truly non volatile. It does not depend on charge storage to function.

3. Phase Three Potassium Nitrate is radiation hard and has definite military significance. The limit factor is the silicon chip required for decoding.

4. Being static, the decoding circuitry should be quite simple.

EXHIBIT
5
SN 793,186
Filed: 10/31/85
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inter-office correspondence

Technovation continued.

I have also attached to this memo a set of miscellaneous Technovation notes for your perusal.

Larry McMillan

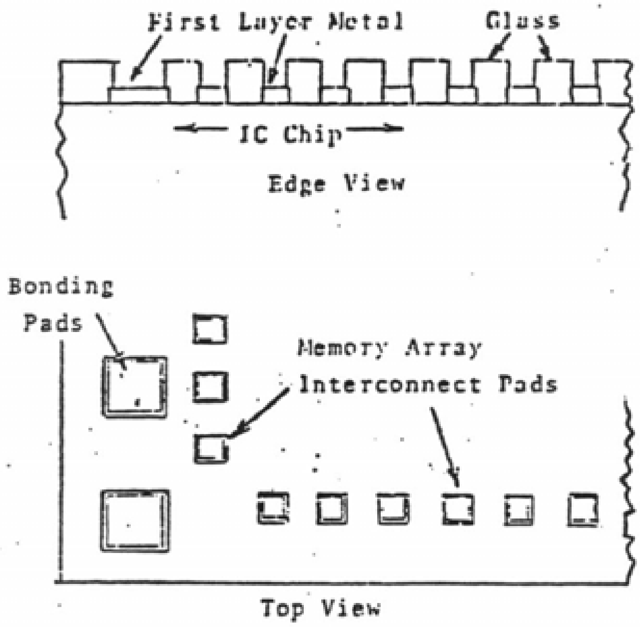

FIGURE 1

1. Standard IC processing may be used through first layer metal. If silicon gate technology is used the first layer interconnection may be poly runs.

2. Deposit CVD glass and cut interconnect pad windows. Vacuum Nitride may be used for this layer if first layer interconnects are poly.

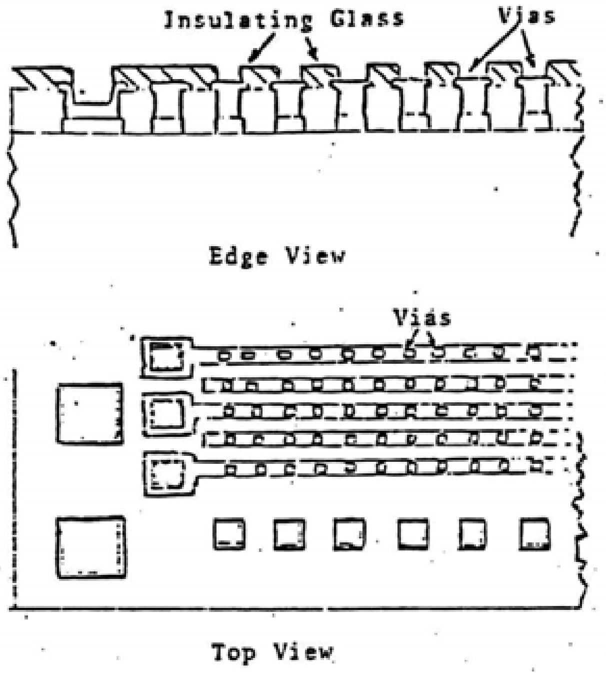

FIGURE 3

5. Deposit CVD insulating glass.

6. Define and etch vias using standard photoresist techniques. (Note figure 3.)

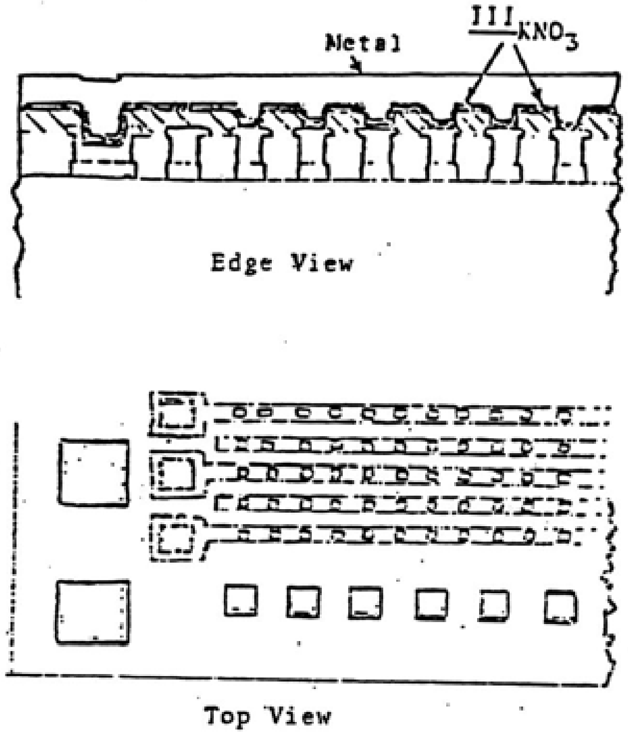

FIGURE 4

7. Evaporate (or deposit) ferroelectric layer and top electrode metal in one pumpdown. Note that phase three KNO_3 reverts to another phase and loses its ferroelectric properties in the presence of moisture.

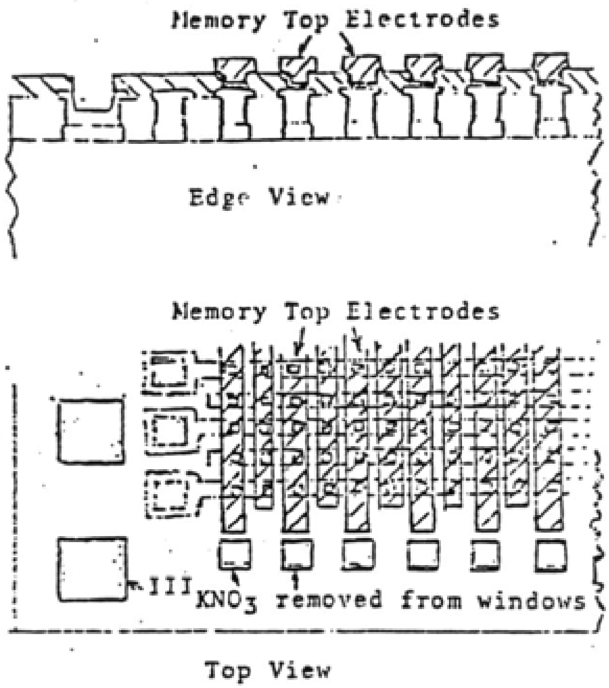

FIGURE 5

8. Pattern top electrodes and partially etch metal. (If top metal is 20KÅ etch 10KÅ only.)

9. Back sputter to clear metal pattern and remove ferroelectric material from undesired areas. (See figure 5.)

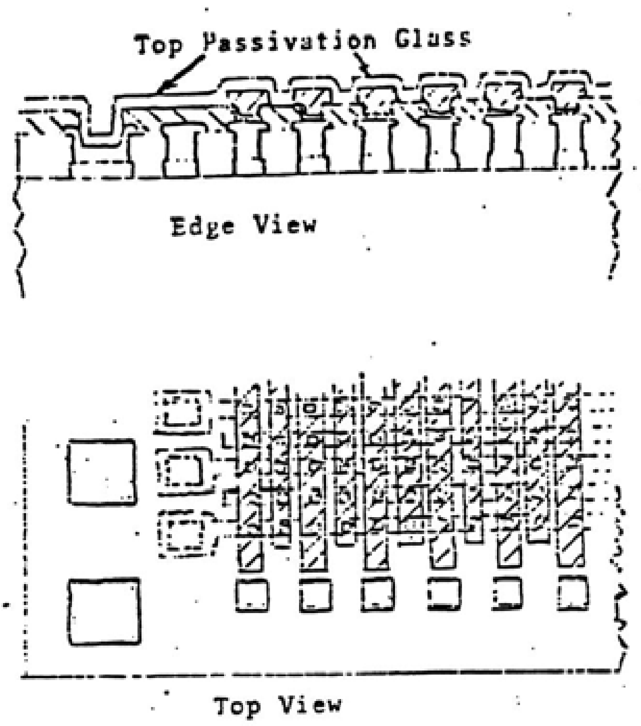

FIGURE 6

10. While still under vacuum, sputter top (passivation) glass layer to prevent moisture contamination of $^{III}KNO_3$. (Figure

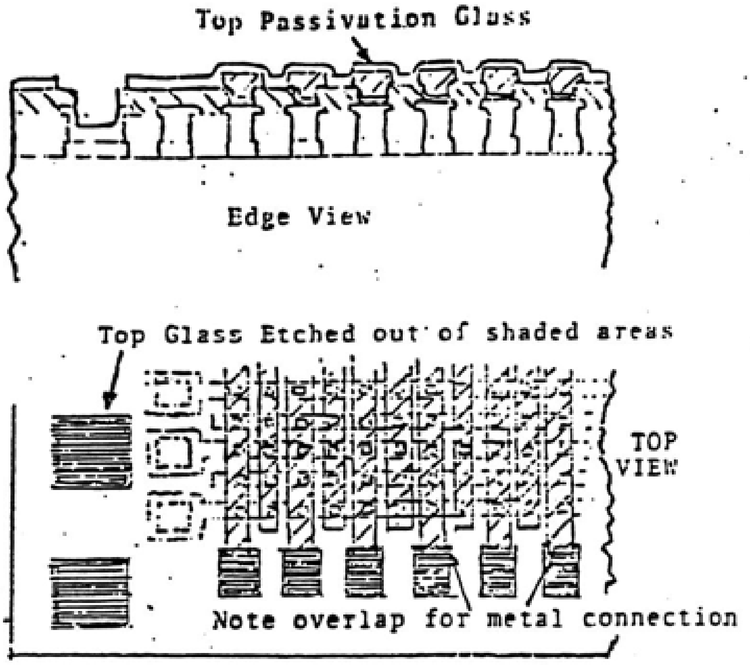

FIGURE 7

11. Pattern and etch top electrode contact areas (and bonding pads) using standard photoresist techniques. Note the overlap of the top glass cut on the top electrode to provide proper contact between the top electrode and the IC chip address circuitry.

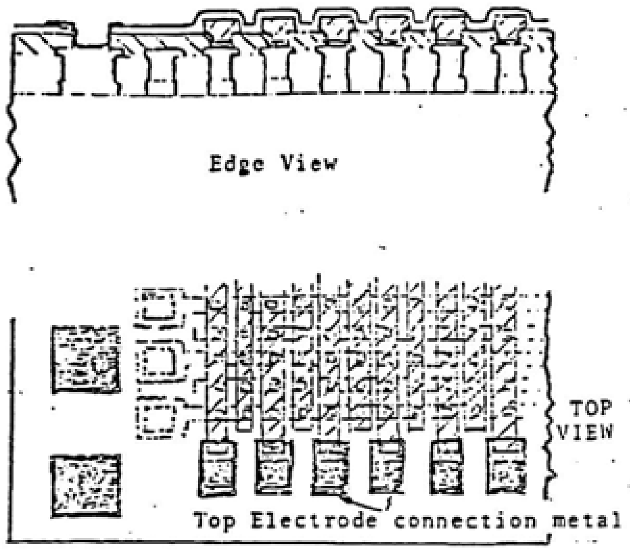

FIGURE 8

12. Evaporate interconnect metal.

13. Pattern and etch interconnect metal using standard photoresi techniques. (see figure 8.)

14. Back lap and gold back.

LDM 8/1/75

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D. McMillan's Corporate Experience

1955-1965 ***Associated Truck Lines*****: Claim Investigator, Dispatcher, Terminal Manager**

1965-1975 ***Motorola, Inc.*****: Bipolar IC Process, Engineer, Manager: Bipolar IC R&D Pilot Line, Manager: Linear IC, Production Engr. Staff Scientist (APRDL)**

1975-1976 ***Motorola, Inc*****.: Manager: NMOS IC, Production Engineering**

1976-1977 ***American Microsystems*****: Manager: CMOS IC Process Engineering**

1977-1979 ***National Cash Register (NCR)*****: Corporate Director of Engineering**

1979-1980 ***Storage Technology Corp.*****: Vice Pres. & General Mgr: Microtech Operations**

1980-1982 ***Stephenson Western Corp.*****: Vice Pres.: Semiconductor Industry Consulting**

1982-1984 ***Honeywell Corp*****.: Manager: MOS IC Operations**

1984-1986 ***Ramtron Corp.*****: Co-Founder, Vice President R&D**

1986-Present ***Symetrix Corp.*****: Co-Founder, President & CEO**

2004-Present ***Nexcard Systems Japan*****: Co-Founder, Board Member**

E. McMillan's 1972 C-V Publication

MOS C-V Techniques for IC Process Control

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(2)

During IC wafer processing a wide range of variables produce a specific desired type of wafer. Often contaminants leak into, or are unknowingly introduced into, the processing procedure. The effect of these contaminants can readily be seen on a capacitance-voltage (C-V) plot such as is used in MOS wafer processing today. However, determining what caused the resultant variation in the C-V plot has been a problem that has plagued the process engineer. An equation of the C-V plot can be formulated that includes the major physical parameter variables involved. This numerical model, which includes Fermi energy level, hole concentrations, etc., can be solved via the iterative method on a computer. The results can be printed out as individual C-V graphs for each set of initial equation parameters. These computer generated theoretical curves can then be matched against actual process C-V plots to determine the nature of contamination.

A NUMBER OF INVESTIGATORS[1,2,3,4] have shown that contaminated oxides render both MOS and bipolar devices unstable. Accumulated positive charges (sodium ions) in the oxide over p-type regions will induce an increased concentration of electrons in the silicon underneath, resulting in a decrease in the net effective acceptor concentration in the surface region. In the extreme case, if sufficient positive ions have piled up to induce more negative charges in the underlying silicon than the original number of acceptor atoms in that region, then an n-type inversion layer is formed. (Metz[4] has calculated that one thousandth of a monolayer of ionic contaminants can invert a high resistivity region.) Negative ions over n-type regions may induce positive charges in the underlying region in a similar manner; however, it is not certain that negative ions are as mobile as positive ions in SiO_2.[3,4]

Metz[4] has shown that mobile ions in the oxide migrate to the Si-SiO_2 interface under the influence of temperature and the presence of the fringing field of a reverse biased junction (Fig. 1). Of course, metal runs that are more positive in potential than the silicon underneath also set up fields in the oxide that can drive positive ions to the Si-SiO_2 interface at elevated temperatures. (Even under normal operating conditions the Si-SiO_2 interface temperature over a reverse biased junction may be high enough for sodium ions to be mobile in that region.[3])

These surface charges affect low current beta, surface recombination velocities, leakage currents and breakdown voltages.[3,4] Long term drift problems and field

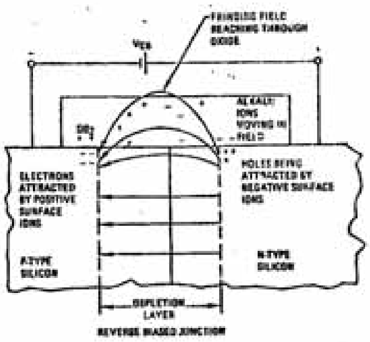

Fig. 1—Mobile ions under the influence of a reverse bias fringing field.[3]

tures are often the direct results of contaminated oxides.

The sources of contamination are many and varied. Contaminated furnace tubes and metal systems, ineffective cleaning systems, and even the workers themselves are all potential sources of contamination. Detection of these sources is not always easy. However, one tool that lends itself readily to the task is the simple MOS capacitor. This report shows how MOS capacitors and a numerical model of their capacitance-voltage (*C-V*) plot can be used for process control. Included is elementary theory necessary to understand and interpret capacitance versus voltage (*C-V*) plots.

Experimental Procedure

Central to the *C-V* process control idea is the fact that the capacitance versus voltage (*C-V*) plots of MOS capacitors are sensitive indicators of contaminants and charges in MOS gate oxides and at Si-SiO_2 interfaces. Since simple MOS capacitors, such as shown in Fig. 2, can be easily manufactured in most IC processing areas, a convenient and reliable tool is readily available for process control. A typical processing sequence might be as follows:

1. Wafers with the desired crystal orientation, dopant and resistivity are selected depending upon the nature of the experiment.
2. The wafers are cleaned with either a standard pre-diffusion clean or a specially devised experimental clean.
3. SiO_2 is grown on the wafers in the furnace being evaluated or in a standardized clean furnace.
4. The wafers are given a pre-metal clean if the period of time between oxide growth and metal evaporation is more than a few hours.
5. Aluminum is evaporated through a metal mask to eliminate the metal photoresist step as a possible source of contamination.
6. *C-V* plots are generated from the resulting MOS capacitors. A block diagram of the apparatus used to generate *C-V* plots is shown in Fig. 3.

Variations in the process at any step in the sequence will be reflected in the *C-V* results. For example, if one wanted to evaluate the effects of a new pre-diffusion cleaning process, some wafers could be processed through the new cleaning cycle holding all other processing steps constant. The *C-V* plots of the MOS capacitors on the new wafers using the new step can then be compared with the *C-V* plots of MOS capacitors manufactured using a standard process cycle. A significant difference in the shape, and/or offset voltage, between the curves of the two processes may indicate that oxide charges or contamination have been introduced by the new cycle.

A *C-V* plot done at room temperature generally yields very little information about the type or quantity of charge involved. It is a common practice, therefore, to use some form of thermal bias stressing to separate the various types of oxide charge. Figure 4 indicates how this may be accomplished. By measuring the resulting

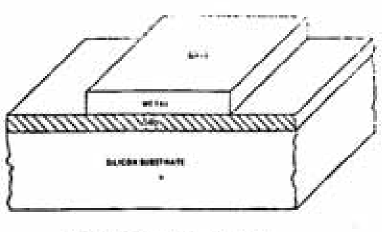

Fig. 2—MOS capacitor cross-section.

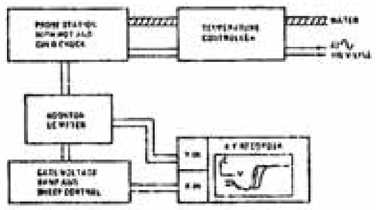

Fig. 3—Block diagram of C-V testing equipment layout.

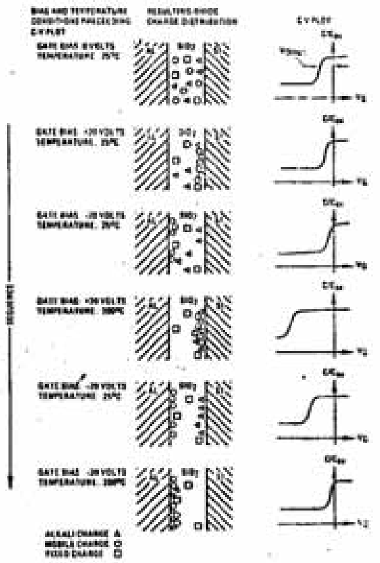

Fig. 4—C-V plots and charge distributions resulting from various temperature-bias conditions (n-type substrate).

shifts along the voltage axis (usually at flatband where the energy bands in the silicon are flat out to the surface) we can derive the amounts of various mobile and immobile charges in the oxide with the formula:

$$\text{Amount of charge} = \frac{\text{Voltage shift at flatband} \times \text{max cap. measured}}{q}$$

where q = charge on one electron.

Beyond a few basic observations, however, the complete analysis of *C-V* curves is usually complicated by anomalies in the curve shapes. In most cases, it is much more meaningful, and certainly easier, to compare the experimental results to a set of theoretical curves derived from manipulation of a mathematical model.

Mathematical Model.

Analysis of C-V Plot

The gate capacitance vesus gate voltage curves for a p-type MOS capacitor may be broken up into three regions as shown in Fig. 5. For a negative gate voltage, majority carriers are induced at the Si-SiO_2 interface so that the capacitance measured in region I is essentially that of the oxide layer. (Refer to Fig. 7 for typical energy band configuration.)

As the gate voltage is increased, a point is reached (point "a" of Figure 5) where the surface potential ψ_s equals zero, and the energy bands are flat out to the surface of the semiconductor. A depletion layer begins to form in the semiconductor when $\psi_s > 0$. The capacitance measured in region II decreases with the series combination of the capacitance of the oxide (C_o) and the capacitance of the substrate (C_s). (Points "a" and "b", Fig. 5.)

Further increase in gate voltage widens the space charge layer until, finally, an inversion-layer consisting of minority carriers (electrons) begins to form at the suface of the semiconductor. This point is called the threshold voltage V_T (point "b" of Fig. 5). Still further increase in positive bias will now increase the number of electrons in the inversion layer but will not appreciably affect the width of the space charge region provided the bias is changed slowly.[8]

If a very large positive bias is applied rapidly at a high frequency (or pulsed), the space charge region will at first become very wide and device capacitance C will approach zero ("b" and "c" in Fig. 5). As minority carriers are generated and the surface comes to equilibrium with the bulk, the space charge will return to its maximum equilibrium width. A surface channel or inversion layer will then form and the capacitance will approach that of the oxide alone (Fig. 5, point "d").

The numerical model described here assumes a low frequency, or dc bias (See Fig. 6). Therefore, the resultant curves will resemble the curve from points "a" through "d" in Fig. 5.

The following calculations assume a p-type substrate, though little modification is necessary for n-type material. In analyzing the MOS structure, a one dimensional situation has been assumed. That is, the structure is considered as a semi-infinite block with all fields directed normal to the interfaces. It has also been assumed that the work function differences across the oxide are negligible. A typical energy band configuration is given in Fig. 7.

Basic to the analysis of MOS structures is a consideration of the surface potential at the Si-SiO_2 interface. This potential can be found as a function of gate voltage by considering the energy band configuration. Once the surface potential has been determined, it can then be

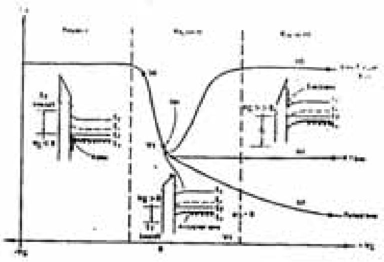

Fig. 5—Gate Capacitance vs. Gate Voltage curves for a p-type MOS capacitor.

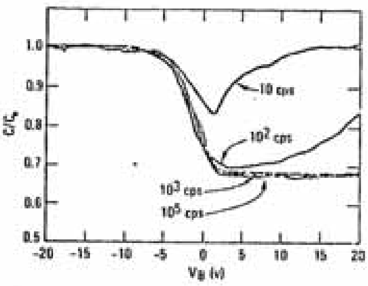

Fig. 6—Effect of measurement frequency on the capacitance-voltage characteristics of an MOS structure.

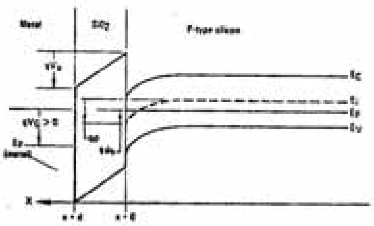

Fig. 7—Typical energy band configuration for a p-type MOS capacitor.

[illegible] capacitance versus voltage with the effects of surface states and charges in the oxide.

Assuming that a single expression for the field in the semiconductor applies for all oxide and interface situations, the charge density, ρ, in the semiconductor may be expressed as:

$$\rho = q(p - n - N_A + N_D) \qquad (1)$$

where
- q = charge in coulombs
- p = hole concentration
- n = electron concentration
- N_A = accepter concentration
- N_D = donor concentration

For the nondegenerate case:

$$p = n_i e^{-(E_F - E_i)/KT} = n_i e^{-q\psi/KT}$$
$$n = n_i e^{(E_F - E_i)/KT} = n_i e^{q\psi/KT}$$

where
- E_F = Fermi energy level
- E_i = Intrinsic Fermi energy level.

Upon substituting the above into Poisson's equation and performing the integration, we obtain Eq. (2) below,

Where
- $E_{ss} > 0$ for $\psi_s < \psi_B$
- $E_{ss} < 0$ for $\psi_s > \psi_B$
- ψ_s = surface electrostatic potential
- ψ_B = semiconductor potential

The oxide layer capacitance per unit area is given by:

$$C_o = \frac{\epsilon_{ox}}{d} \qquad (3)$$

where
- ϵ_{ox} = permitivity of SiO_2
- d = thickness of SiO_2

and the semiconductor depletion-layer capacitance is given by:

$$C_s = \left|\frac{dQ_{si}}{d\psi_{si}}\right| \qquad (4)$$

where Q_{si} is the net charge per unit area in the semiconductor.

To determine C_s as a function of ψ_s, we first establish Q_{si}:

$$Q_{si} = \int_{-\infty}^{0} \rho(x)\,dx = \int_{\psi_B}^{\psi_s} \frac{\rho}{d\psi/dx}\,d\psi \qquad (5)$$

Substituting Eqs. (1) and (2) into (5) and integrating, we obtain Eq. (6) below,

where
- $Q_{si} < 0$ for $\psi_s > \psi_B$
- $Q_{si} > 0$ for $\psi_s < \psi_B$

Differentiating Eq. (6) with respect to ψ_s gives us Eq. (7) below.

The total low frequency capacitance is the series combination of C_o and C_s:

$$C = \frac{C_o C_s}{C_o + C_s} \qquad (8)$$

where
- C_o = oxide capacitance
- C_s = silicon surface space charge capacitance

In order to obtain an expression for the surface potential as a function of gate voltage we must consider the field in the oxide, and then match the fields at the interface. In this way, both surface states and charge in the oxide will be taken into account.

For purposes of analysis let us consider a single level of donor type surface states at the Si-SiO_2 interface. These states are neutral when occupied and have a positive charge when not. Their position relative to energy band midgap is denoted by ϕ_{ss} and their density by N_{ss}. The surface state charge per unit area is then given by:

$$Q_{ss} = qN_{ss}\frac{1}{1 + e^{q(\psi_s + \phi_{ss})/KT}} \qquad (9)$$

which is just q times the density of unoccupied states.

Any number of oxide charge distributions may be considered; however as an example, we will consider here only a positive oxide charge with its density a linear function of x as shown in Fig. 8.

$$E_{ss} = \pm\left[\frac{4n_iKT}{\epsilon_{si}}\left(\cosh\frac{q\psi_s}{KT} - \cosh\frac{q\psi_B}{KT}\right) + \frac{2qN_A}{\epsilon_{si}}(\psi_s - \psi_B)\right]^{\frac{1}{2}} \qquad (2)$$

$$E_{ss} = -\frac{d\psi}{dx} \text{ (electrostatic field at the surface of the semiconductor)}$$

$$Q_{si} = \pm\left\{2\,\epsilon_{si}\left[2\,n_iKT\left(\cosh\frac{q\psi_s}{KT} - \cosh\frac{q\psi_B}{KT}\right) + qN_A(\psi_s - \psi_B)\right]\right\}^{\frac{1}{2}} \qquad (6)$$

$$C_s = \left|\frac{dQ_{si}}{d\psi_s}\right| = \pm\frac{2n_iq\left(\sinh\frac{q\psi_s}{KT}\right) + qN_A}{\left[\frac{4n_iKT}{\epsilon_{si}}\left(\cosh\frac{q\psi_s}{KT} - \cosh\frac{q\psi_B}{KT}\right) + \frac{2qN_A}{\epsilon_{si}}(\psi_s - \psi_B)\right]^{\frac{1}{2}}} \qquad (7)$$

Then,

$$N(x) = \frac{N_o}{d}(d - x);\ \rho = qN(x) \qquad (10)$$

Therefore

$$\frac{d^2\psi}{dx^2} = -\frac{\rho}{\epsilon_{ox}} = -\frac{q N_o}{\epsilon_{ox} d}(d - x) \qquad (11)$$

The boundary conditions necessary are:

$$\left.\frac{d\psi}{dx}\right|_{x=0} = -E_{ox}$$

$$\psi(x=0) = \psi_s$$

$$\psi(x=d) = \phi(x=d) + \psi_B = V_G + \psi_B$$

where ϕ = electrostatic potential relative to the intrinsic Fermi level in the bulk.

This latter condition follows from the fact that there can be no change in potential across the external loop except the potential applied to the gate; therefore, $\phi(x=d) = V_G$. Integrating equation (11) twice and evaluating the integration constants from the boundary conditions, we obtain Eq. (12) below.

In Eqs. (2), (9) and (12), we now have expressions for fields on both sides of the $Si\text{-}SiO_2$ interface as well as for charge at the interface. These may be related as:

$$\epsilon_{ox} E_{ox} - \epsilon_{si} E_{si} = Q_{ss} \qquad (13)$$

With a little juggling this equation becomes Eq. (14) below where, on the right side of Eq. (14), the positive sign applies for $\psi_s > \psi_B$, the negative for $\psi_s < \psi_B$.

Solution of Model Equation

Note in Eq. (14) that $\frac{\epsilon_{ox}}{d} = C_{ox}$, the capacitance per unit area of the oxide layer. Thus the *first term* on the left of the equation is just the charge stored on the gate electrode, since the net potential drop across the oxide is given by:

$$\psi(x=d) - \psi(x=0) = V_G - \psi_s + \psi_B$$

In fact, this term is always present, independent of oxide charge or surface states. The *second term* on the left of Eq. (14) results from the charge distribution in the oxide and depends on both the magnitude and shape of this charge distribution. The *third term* represents the effect of the surface states. There will be one such term corresponding to each surface state level, at a position ϕ_{ssi} with density N_{ssi}. Equation (14) is not easily solved for ψ_s in closed form, but it can be handled iteratively by computer. The total capacitance as a function of gate voltage easily follows from Eqs. (7) and (8).

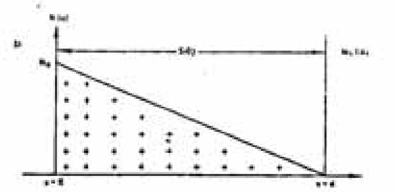

Fig. 8—A positive oxide charge with its density a linear function of x.

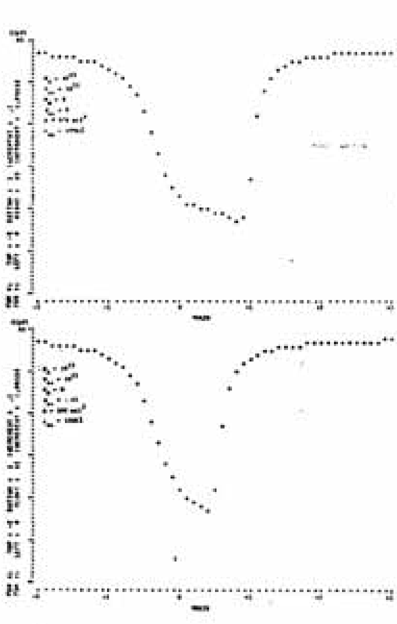

Fig. 9—Sample theoretical C-V plots.

By using one of many computer function plotting programs now widely available, an entire catalog of theo-

$$E_{ox} = -\left.\frac{d\psi}{dx}\right|_{x=0} = -\left(\frac{V_G - \psi_s + \psi_B}{d} + \frac{q N_o d}{3\epsilon_{ox}}\right) \qquad (12)$$

$$\frac{\epsilon_{ox}}{d}(V_G - \psi_s + \psi_B) + \frac{q N_o d}{3} + q N_{ss}\frac{1}{1 + e^{q(\psi_s + \phi_{ss})/KT}} = \pm\left\{2\epsilon_{si}\left[2 n_i KT\left(\cosh\frac{q\psi_s}{KT} - \cosh\frac{q\psi_B}{KT}\right) + qN_A(\psi_s - \psi_B)\right]\right\}^{\frac{1}{2}} \qquad (14)$$

retical C-V curves can be generated. Examples of plots, showing the effects of changing some of the variables, are given in Fig. 9

Interpretation of a new process C-V plot now becomes simply a matter of matching experimental curves with one of the computer generated theoretical curves.

Summary and Conclusions

This report has presented a simple method of using MOS C-V techniques for process control. Sufficient theory has been developed to generate theoretical low-frequency C-V curves for comparison with experimental results. It seems evident that this is a powerful tool for evaluating the influence of process parameters on the properties of SiO_2 films and SiO_2 interfaces, and that it could be used more extensively in wafer processing areas.

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List of Symbols Used

ψ	Electrostatic potential relative to the Fermi level in the bulk of the semiconductor
ψ_B	ψ in the semiconductor ($\psi = \psi_B$ as $X \to -\infty$)
ψ_S	ψ at $X = 0$
V_O	Potential drop across the oxide layer
Q_{ss}	Surface state charge/unit surface area
E_i	Intrinsic Fermi level energy
E_F	Fermi level energy
E_C	Conduction band energy
E_V	Valence band energy
ϕ	Electrostatic potential relative to the intrinsic Fermi level in the bulk
p	Hole concentration in the semiconductor
n	Electron concentration in the semiconductor
V_G	Applied gate-substrate voltage
ϕ_{ssi}	Position of surface state i in the energy gap relative to midgap
N_s	Reference density for charge in the oxide
N_{ssi}	Density of states in level i
N_A	Acceptor concentration
N_D	Donor concentration
E_s	Electrostatic field in semiconductor
E_{ss}	E_s at $X = 0$ (the surface of the semiconductor)
E_{ox}	E_s at $X = 0$
ϵ_{ox}	Permittivity of SiO_2
ϵ_{si}	Permittivity of silicon
C_o	MOS capacitance due to oxide capacitor
C_s	Capacitance due to the space charge region at the surface of the silicon

F. McMillan's 1994 LSMCD BST Publication

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DEPOSITION OF BARIUM STRONTIUM TITANATE AND STRONTIUM TITANATE VIA LIQUID SOURCE CHEMICAL VAPOR DEPOSITION

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(Received March 5, 1994)

Liquid Source Chemical Vapor Deposition (LSCVD) involves the use of sub-saturated aerosols of specially designed metallorganic precursors suitable for multicomponent oxide deposition in vacuum at room temperature. Materials of interest for ULSI DRAMs, such as $Ba_{(1-x)}Sr_xTiO_3$ and $SrTiO_3$ show uniform deposition with microstructures optimized for step-coverage and small capacitor geometries. Electrical characteristics indicate capacitance densities of around 25–30 fF/um² and leakages in the order of 10^{-8} A/um². A review of these results and the LSCVD technique will be presented.

Keywords: ~~Keywords to be provided with return page proofs~~ [redacted]
BST, CVD, MIST

INTRODUCTION

It is generally acknowledged that future ULSI DRAMS will require charge storage densities far beyond what can presently be achieved with conventional silicon dioxide (or silicon nitride) dielectrics. We easily see from Figure 1 that the integrated circuit industry must move to new high dielectric constant materials if such devices are to be built within reasonable design, process and economic constraints in the near future.

There appears, however, to be a general reluctance in the IC industry to move away from the well understood and well characterized silicon dioxide (or silicon nitride) dielectric system. Choosing the right material for ULSI DRAMS is not an

DRAM CAPACITOR MATERIALS

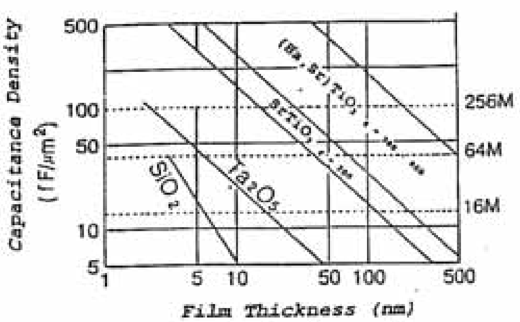

FIGURE 1 DRAM capacitor materials.

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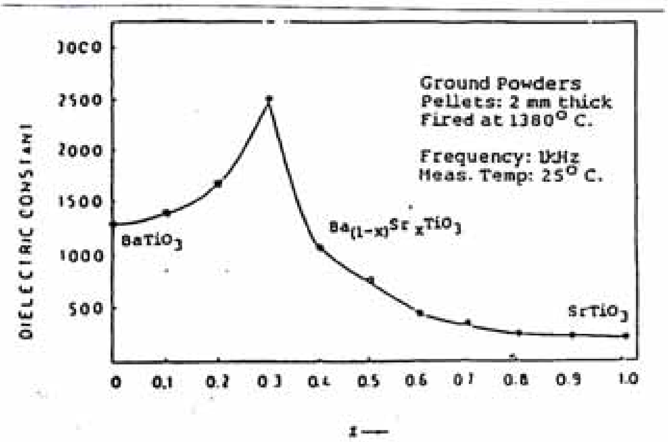


FIGURE 2 Barium strontium titanate: dielectric constant as a function of stoichiometry (Reference 1).

easy task. Many of the new (proposed) high dielectric constant materials have very complex, multi-component structures that are difficult to synthesize and contain elements that are normally considered to be contaminates or hazardous in a processing area. Some of the well known high dielectric constant materials (such as lead zirconate titanate) exhibit ferroelectric properties such that the dielectric constant decreases significantly at high frequencies. In general, most of these new materials are difficult to produce consistently with existing thin film deposition equipment.

As indicated in Figure 1, it appears that barium strontium titanate and/or strontium titanate could easily satisfy the requirements for the next generation of ULSI DRAMS. Rather high dielectric constant values have been reported for these materials in hot pressed ceramic form (refer to Figure 2), and several companies have already begun evaluation of various thin-film deposition techniques for prototype production.[1-3] In the following, we report the results of our efforts to deposit thin-films of these materials using Liquid Source CVD.

LIQUID SOURCE CVD

In 1991 we demonstrated the use of a deposition machine that injected liquid sol-gel material into a vacuum chamber at room temperature for the production of high quality lead zirconate titanate (PZT) thin films.[4] This year we have modified the machine to produce high dielectric constant strontium titanate and barium strontium titanate films of sufficient quality for DRAM (planar capacitor) applicaitons.

The Symetrix Liquid Source CVD (LSCVD) machine is designed around the concept of introducing stoichiometrically correct compound liquid sources into a

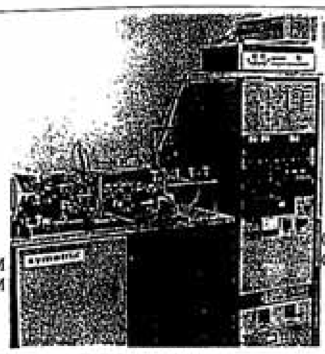


FIGURE 3 Symetrix LSCVD Machine as presently configured.

- Ultrasonic Source Temperature (°C.): RT-50
- Base Pressure Prior to Deposition: 1×10^{-8}T.
- Base Pressure During Deposition (mm Hg*): 500-600
- Substrate/Vacuum Chamber Temperature During Deposition: RT
- Deposition Rate (Angstroms/Min): 35-100
- Post Processing Pressure (mm Hg*): 200-400
- Following vacuum deposition, all films are furnace annealed in oxygen at temperatures between 550-850°C.

*Atmospheric Pressure: 760 mm Hg

FIGURE 4 Typical processing parameters for strontium titanate and barium strontium titanate.

vacuum chamber to form thin films at room temperature. The original machine has evolved through actual practice to that shown in Figure 3. As generally configured, an ultrasonic transducer is used to drive sol-gel, MOD and/or other solutions into a "mist," which is then injected, along with an inert carrier gas, into a vacuum chamber. Inside the vacuum chamber the mist is distributed evenly over a rotating substrate. Additional operating details may be found in Reference 4.

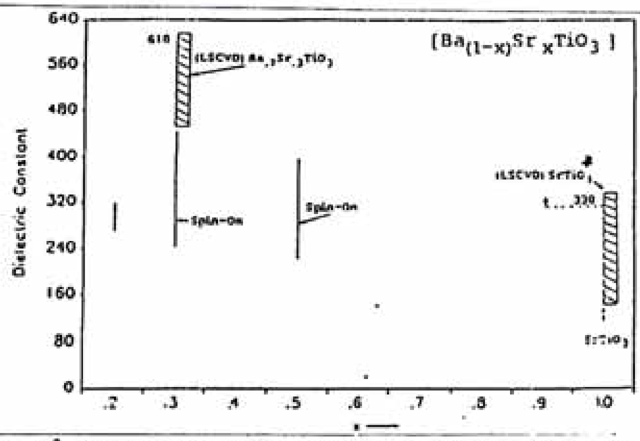
In order to deposit strontium titanate and barium strontium titanate with this machine, we found that it was necessary to modify the deposition chamber such that the mist was forced to settle more efficiently onto the substrate.[5] These modifications ultimately resulted in uniform films (5–10% thickness variability across a 4" wafer) using the operating conditions shown in Figure 4.

EXPERIMENTAL RESULTS

Figure 5 shows the results of depositing a 140 nm film of barium strontium titanate by LSCVD over a 220 nm metal step. It should be noted that such depositions are

140 nm (LSCVD) $Ba_{.8}Sr_{.2}TiO_3$ deposited over 220 nm Pt

FIGURE 5 Step coverage of LSCVD deposited barium strontium titanate.



A: 2916μm^2 THICKNESS: 120-160 nm ANNEAL: 650-750 °C O_2

FIGURE 6 Liquid source CVD vs. spin-coating: dielectric constant vs. stoichiometry. *Dielectric constant quite high.

conformal over the top of the step and tend to fill in the solid angle at the bottom of the step. These results are preliminary and further work with Matsushita Electronics Corporation has shown that LSCVD films are superior to spin-on films.[6]

Approximately 100 wafers with barium strontium titanate integrated capacitors were built with liquid sources to compare the results of spin-coating vs. LSCVD deposition. (All electrodes were sputtered platinum.) Figure 6 shows the resulting dielectric constants achieved as a function of $Ba_{(1-x)}Sr_xTiO_3$ stoichiometry. In all cases, the films deposited by LSCVD exhibited slightly higher dielectric constants than those deposited by spin-coating.

Figures 7 and 8 show typical leakage currents achieved with LSCVD deposited films of strontium titanate and barium strontium titanate. At this time, detailed comparisons are being made between LSCVD and spin-on films. Preliminary results are very favorable for the LSCVD films and further details will be published in the near future.

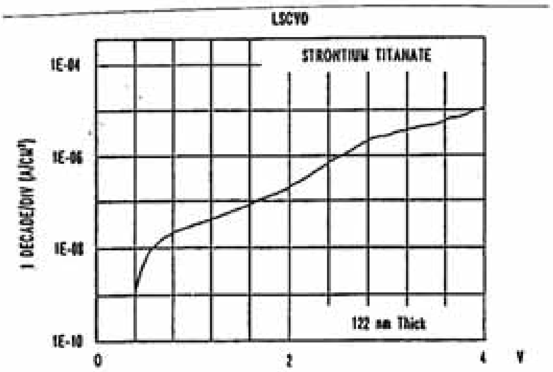


FIGURE 7 Typical leakage current vs. voltage for LSCVD deposited strontium titanate.

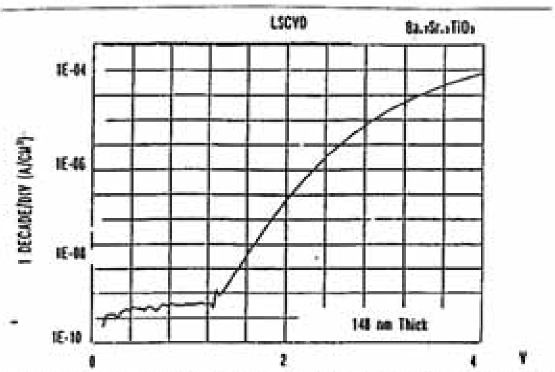


FIGURE 8 Typical leakage current vs. voltage for LSCVD deposited barium strontium titanate.

CONCLUSIONS

We have shown that very good strontium titanate and barium strontium titanate films can be deposited via LSCVD. This paper has been a preliminary report on results obtained by LSCVD. A much more detailed analysis is forthcoming. We have now achieved sufficient success with this method of deposition for complex films on four inch wafers to warrant construction of a new LSCVD machine for six inch wafers. This new (six inch) machine has been built and is currently used for prototype production of integrated circuits requiring ferroelectric and high dielectric constant films.

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