Bo Lojek

History of Semiconductor Engineering

Bo Lojek

History of Semiconductor Engineering

With 319 Figures, 1 in Color

Springer

Dr. Bo Lojek
ATMEL Corporation
1150 E. Cheyenne Mtn. Blvd.
Colorado Springs, CO 80906, USA
e-mail: blojek@atmel.com

Cover Illustration: Layout of Fairchild analog integrated circuits prepared by Dolores Talbert (Circa 1963)

Library of Congress Control Number 2006938040

ISBN-10 3-540-34257-5 Springer Berlin Heidelberg New York
ISBN-13 978-3-540-34257-1 Springer Berlin Heidelberg New York

Springer is a part of Springer Science+Business Media
springer.com

Typesetting: PTP-Berlin Protago-TEX-Production GmbH, Germany
Cover-Design: WMXDesign GmbH, Heidelberg
Production: LE-TEX Jelonek, Schmidt & Vöckler GbR, Leipzig, Germany

Printed on acid-free paper 7/3100/YL - 5 4 3 2 1 0

To the memory of my parents, Bohumila and Rudolf Lojek.
Because memory remains.

Preface – The pages that should be read first

The innovator makes enemies of all those who prospered under the old order, and only lukewarm support is forthcoming from those who would prosper under the new, because men are generally incredulous, never really trusting new things unless they have tested them by experience.

Niccolo Machiavelli, The Prince

Many years ago I was called to jury duty. During the jury selection, the plaintiffs' attorney asked my name and what I did for a living. I was very proud of my profession and what I did and I answered my name and said "*I am an engineer.*" The attorney did not ask any other questions and without hesitation said that I could go because he did not want me as a member of the jury. On the way home I was pondering what was wrong with engineers that they are not suitable for jury duty. If I had answered the attorney's question that I was a car salesperson or politician he would have considered me for jury duty – but not if I was an engineer.

My dad was an engineer; he could fix everything. He regularly took me to all kinds of junk yards and we always found something that was worth bringing home. I was taught to pick up screws or washers on the street, because after cleaning it certainly could be used again. I knew very early on that I wanted to be an engineer like my dad. I knew that being an engineer was a noble job. I studied hard and I became an engineer, and now I have faced the situation that I could not be a member of a jury because of my profession.

I decided to contact the plaintiffs' attorney and I asked if he could talk to me. We met and I told him my concern. He laughed and told me "*You cannot be a member of a jury, because you are an engineer. Engineers are too analytical and too logical. There is nothing personal.*" Good engineers approach life differently from others. They are analytical and logical, they rather trust the data and experimental evidence than loaded opinion of the attorney.

Anyone who knows anything about engineering would agree that engineers play critical, ubiquitous roles in sustaining our nation's international competitiveness, in maintaining our standard of living, in ensuring a strong national security, in improving our health, and in protecting public safety. The word "engineer" comes from the same Latin word *ingenium* as the words "genius" and "ingenious." I cannot think of any other profession that affects our lives in so many vital, significant ways. Engineers believe in numbers, in the laws of physics, laws of nature; yes, engineers are too analytical and too logical! An attorney would characterize these traits as negative or undesirable qualities, yet I believe they are essential to innovation and progress, and they are qualities of the people who contribute most to our society.

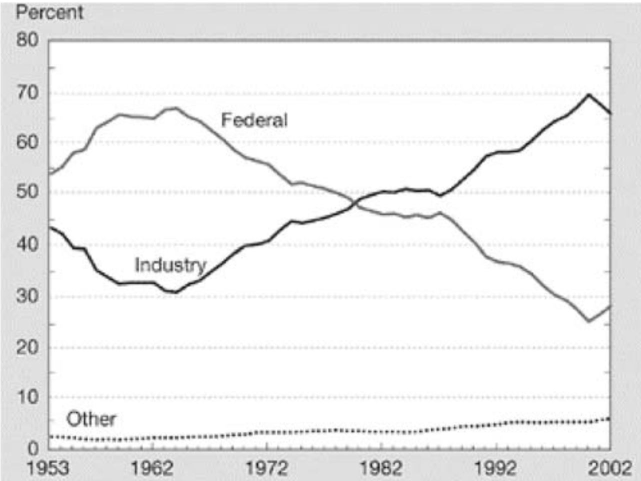


Fig. 1. National R&D expenditures 1953–2002 [Source: National Science Foundation 2004]

Creative people are sometimes seen as eccentric because they *genuinely enjoy* their work, instead of working only because they need an income. They are very seldom motivated by money. Society has changed recently so much that it is not easy to be a good engineer. Our "politically correct" society seems to delight in making it more difficult by denying resources to creative people who need them (Fig. 1.)

The growth of R&D investment in the United States has slowed steadily during the last forty years. Government data indicate that although total R&D expenditures continued to rise through 2002, industrial R&D, which fueled the growth over the prior period, failed to keep pace with inflation and experienced its first decline in real terms after 1994. This has occurred only six times in the past 49 years. The business activities of many R&D-

performing firms were curtailed following the stock market decline and the subsequent economic slowdown of 2001 and 2002.

The Federal Government was once the main source of the nation's R&D funds, funding as much as 66.7 percent of all U.S. R&D in 1964. The Federal share first fell below 50 percent in 1979, and after 1987 it fell steadily, dropping from 46.3 percent in that year to 25.1 percent in 2000 (the lowest it has ever been since 1953). Adjusting for inflation, Federal support decreased 18 percent from 1987 to 2000, although in nominal terms, Federal support grew from $58.5 billion to $66.4 billion during that period. Growth in industrial funding generally outpaced growth in Federal support, leading to the decline in Federal support as a proportion of the total.

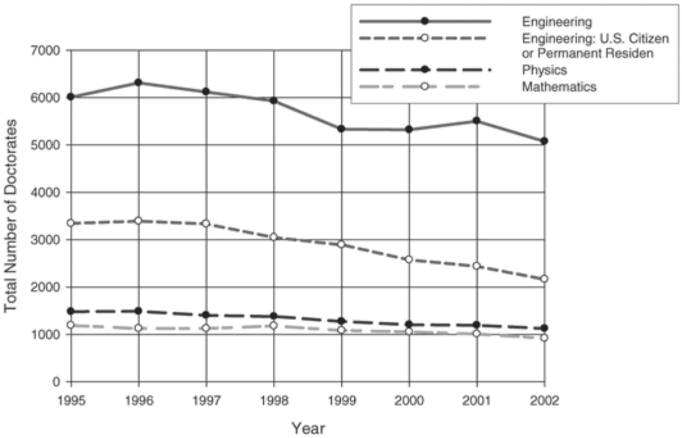


Fig. 2. Doctorates awarded in Engineering, Physics, and Mathematics: 1995–2002 [Source: National Science Foundation NSF 04–303 (October 2003)]

Figure 1 explains the most significant change in the industry which occurred in the early sixties. The industry, with pressure from Wall Street, could not finance long-range and risky basic research. The objective of basic research is to gain more comprehensive knowledge or understanding of the subject under study without specific applications in mind. Basic research advances scientific knowledge but does not have specific immediate commercial objectives. Basic research can fail and often will not bring results in a short period of time. The industry is mainly involved in the Research & Development (R&D), which is the systematic use of the knowledge or understanding gained from basic and applied research directed toward the production of useful materials, devices, systems, or methods, including the design and development of prototypes and processes.

Future American technology projects will be developed here only in the initial stages. Once the cost, rather than innovation, becomes the principal

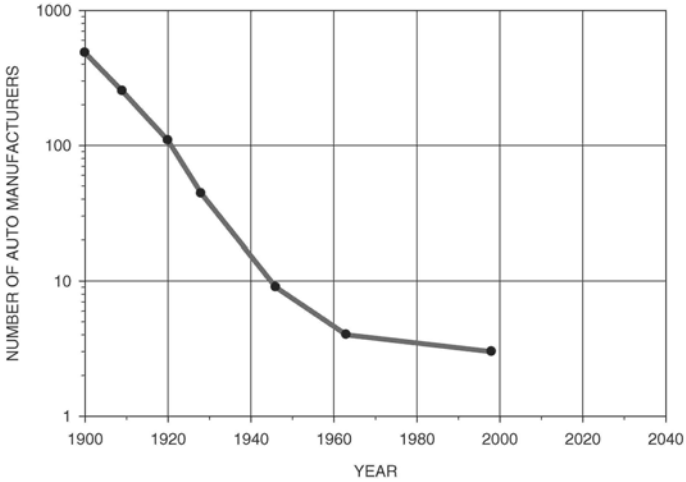


Fig. 3. Automobile Manufacturers in U.S. (1900 – Present)

factor for products, companies will ship the work to cheap-labor countries. So called “outsourcing”, a result of a traditional capitalist economic development life cycle, deflects bright students away from engineering. Not surprisingly, the total number of doctorates awarded in U.S. during 1995 to 2002 in Engineering, Physics and Mathematics during the last decade steadily declined (Fig. 2.)

I was one of the fortunate engineers who had fun all of my life. My parents supported me in all I wanted to do. I enjoyed work constantly; I do not remember a time when I had a vacation. As a boy I built a crystal radio, a superheterodyne, and radio controlled airplanes. As a man, I look forward to being at work every morning. If I had a chance to live my life again, I would not change one iota. Engineering is my passion.

I wrote book about engineers. To be more explicit, this is a book about the group of engineers and scientists who invented modern transistors and integrated circuits. Historians assigned the invention of integrated circuits to Jack Kilby and Robert N. Noyce. In this book I am arguing that the group of inventors was much bigger. It happened that I know or I worked with many of the personalities described in the next chapters. I am describing the events which I lived through.

Colorado Springs, 2002–2006 Bo Lojek

Acknowledgement
Everybody who has written a book knows how difficult writing is. I know how difficult it is to write a book in a second language. I would not have been able to do it if many colleagues at Atmel Corporation where I work had not helped me. However, there are three friends who deserve special recognition:

Robert A. Pease, a distinguished engineer of National Semiconductor, helped me with proofreading and mainly encouraged me when I was in my "low." Bob is also known as "a common sense engineer" and has invented 25 integrated circuits, holds 21 patents, and has written numerous technical papers and books. He authored in Electronic Design over 240 columns and counting. Bob Pease is not only a terrific engineer and a unique personality; he is also the "Czar of Proofreading" who knows the English language, as everything that Bob does, perfectly.

The help and advice of Professor Hans-Joachim Queisser, former Shockley Semiconductor Laboratories employee and one of the founding directors of the Max Planck Institute for Solid-State Physics in Stuttgart, was critical in the final stage of book production.

Dr. Morgan Sparks, Former Bell Laboratorie's scientist, good friend of Bill Shockley, designer of the world's first junction transistor, and retired president of Sandia Laboratories guided me through many obstacles because "*my viewpoints lead to different stories and credits from those generally accepted by the media.*" During the four years of working with Morgan, I found not only my role model but I, also, recognized the nobility of engineering if carried out by a person like Dr. Sparks. I was very glad that at the end of my research I passed Morgan's criteria, and he concluded "*The book is a remarkably detailed account of accomplishments that constitute semiconductor microelectronics.*"

The majority of materials reproduced here is from my archives. I have saved for all my life newspaper clippings, photographs, vacuum tubes, silicon substrates, transistors, pieces of manufacturing equipment, wafers, integrated circuits, Rubylith foil with the mask of my first IC, etc. The paperwork alone grew during the last forty years to 672 cubic feet. When I was young, I never thought about writing a book; I was poorly organized and often, when I pulled out a page from trade magazines or newspapers, I did not record the title and date of publication. For this reason, I was not able to trace all owners of copyright material. However, the copyright holder has released the majority of images used here into the public domain, its copyright has expired, or it is ineligible for copyright.

The author is very much indebted to Ms. Alice Blanck of Springer and Ms. Steffi Hohensee of LE-TEX for their substantial contributions to the heavy task of dealing with a stubborn author, and with putting the manuscript with complicated archive materials into a finished book.

Contents

Prologue

> *"Who controls the past controls the future. Who controls the present controls the past."*
>
> *George Orwell, 1948*

On July 1, 1948 The New York Times printed, on page 48 in the "News of Radio" section, an announcement that NBC would broadcast Waltz Time on Friday night. The same section contains a brief report about a new invention, *"a device called a transistor, which has several applications in radio where a vacuum tube ordinarily is employed."*

When creative men started working on semiconductors by the late thirties and integrated circuits at the end of the fifties, they did not know that they were going to change the lives of future generations. Very few people at that time recognized the significance of perhaps the most important invention of the century. Nobody noticed that the key people behind the inventions were frequently frustrated and disappointed. Who remembers today, names such as Russell Ohl, Karl Lark-Horovitz, William Shockley, Carl Frosch, Lincoln Derick, Calvin Fuller, Kurt Lehovec, Jean Hoerni, Sheldon Roberts, Jay Last, Isy Haas, Bob Norman, Dave Allison, Jim Nall, Tom Longo, Bob Widlar, Frank Wanlass, Federico Fagin, or Dave Talbert?

In the beginning of the sixties the editors of Time-Life Books in Alexandria, V. A. published "A golden Age of Entrepreneurship" with a photograph (Fig. 1) accompanied by a legend stating "1958–1959 Robert Noyce, Jean Hoerni, Jack Kilby, and Kurt Lehovec all took part in developing the integrated circuit".

In Jack Kilby's speech to the 2000 Nobel Prize Committee the names reduced to just Robert Noyce despite the fact that Hoerni and Lehovec's ideas were so much more practical than Kilby's that even Texas Instruments adopted them.

Fig. 1. Inventors of integrated circuit as they were recognized in the early sixties

Neither Hoerni nor Lehovec had the backing of a large company. Approximately 40% of all newspaper stories originate from Press Releases prepared by Public Relation firms. Because radio and TV agencies only re-edit newspaper stories, a substantial portion of the public's "news" originates from PR releases. Naturally the connection to the PR source along with some of the people who created history are edited out.

The idea of the integrated circuit is almost as old as the transistor. For example, in October 22, 1952, Bernard M. Oliver filed a patent application with the idea to integrate several transistors onto one chip. A few months later on May 21, 1953 Harwick Johnson of Radio Corporation of America described "Semiconductor Phase Shift Oscillator and Device," now U.S. Patent # 2,816,228 (Fig. 2). To my knowledge, Johnson's patent represents the very first effort to integrate various electronic components into one piece of material.

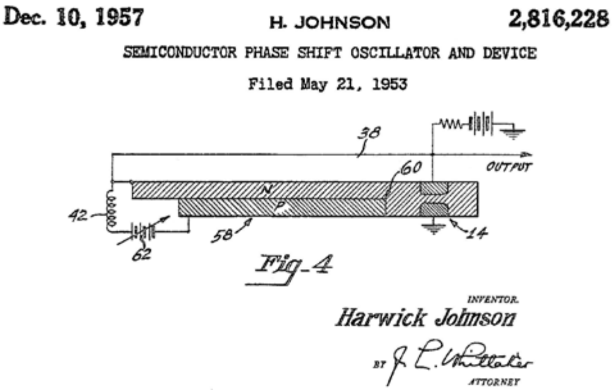


Fig. 2. Harvick Johnson Patent filed May 21, 1953

In May 1952 the British scientist G. W. A. Dummer made the following prediction at the IRE annual electronic components meeting in Washington, D.C. "With the advent of the transistor and the work in semiconductors generally, it seems now to be possible to envisage electronic equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying and amplifying materials, the electrical functions being connected by cutting out areas of the various layers". In the summer of 1957, Dummer described at an International Symposium on Electronics Components at Malvern, UK "a transistor flip-flop with two emitter follower outputs – a total of four transistors all contained in a chip of silicon 125 mils by 375 mils." Dummer's idea was using a loose wire to connect all circuit components. Johnson described in 1953 the same circuit as Jack Kilby of Texas Instruments many years later, and the similarity of these circuits is more than obvious from the comparison shown in Fig. 3. The natural question which probably most people would ask is, "What is the difference between the Johnson and Kilby application that allowed the invention priority to go unequivocally to Kilby?" It is not easy to answer such a question. Johnson described his circuit as a "unitary body" where much of the conventional circuitry is eliminated. Kilby used the term "circuit integrated into the body of material."

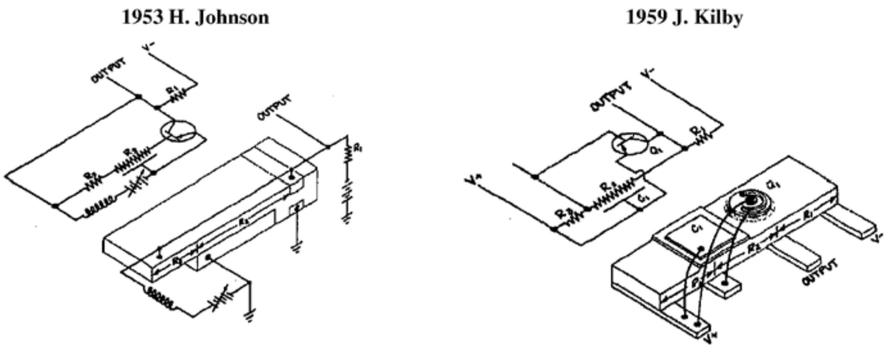


Fig. 3. Comparison of Johnson and Kilby Patents

Kilby's idea of the integrated circuit was so unpractical that it was dropped even by Texas Instruments. Kilby's patent was used only as very convenient and profitable trading material. Most likely, if Jack Kilby worked for any company other than Texas Instruments, his idea would never have been patented.

All innovative and astonishing ideas in semiconductor engineering are the products of very creative individuals. Creative individuals, not business leaders or government initiatives, are the most important factor in creating new devices. The current "politically correct" society and PR departments of large companies alter historical events, and present a development of what is today called microelectronics as a systematic effort of exceptional leadership. Many modern college business textbooks list companies such as Fairchild Semiconductor Corporation and Geophysical Service Inc. (later re-named to Texas Instruments) as examples of exceptional business wisdom.

2,816,228

SEMICONDUCTOR PHASE SHIFT OSCILLATOR AND DEVICE

Harwick Johnson, Princeton, N. J., assignor to Radio Corporation of America, a corporation of Delaware

Application May 21, 1953, Serial No. 356,407

10 Claims. (Cl. 250—36)

In the electron tube art, it is well known that a tube may be operated, in a suitable circuit, as a phase-shift oscillator. In such circuits, a resistance-capacity phase shifting network is connected between the output and the input of an amplifier tube, the circuit being proportioned to provide a 180° phase shift at the desired oscillation frequency. In accordance with the invention, a transistor may be similarly operated in such an external phase-shifting circuit. Also in accordance with a preferred embodiment of the invention, a semiconductor phase-shift oscillator is incorporated in a unitary body whereby much of the circuitry of the conventional phase-shift oscillator is eliminated.

The capacitance of a P-N junction biased in the reverse direction may be determined from the formula:

$$C=\frac{KA}{4\pi W}$$

wherein:

K=dielectric constant of the semiconductor material
W=thickness of the P-N junction
A=cross-section area of the P-N junction

The capacitance of a P-N junction biased in the forward direction may be determined from the formula:

$$C=\frac{qL^2I}{kT4D}$$

wherein

q=magnitude of electron charge
L=diffusion length of minority carriers
k=Boltzmann's constant
T=temperature in degrees Kelvin
D=diffusion constant
I=current

The resistance of a piece of semiconductor material may be determined from the formula:

$$R=\frac{rL}{A}$$

wherein:

r=resistivity of the semiconductor material
L=length of the piece
A=cross-section area of the piece

What is claimed is:

1. A semiconductor device comprising a body of semiconductor material having alternating zones of different conductivity material and a semiconductor delay line integral with one of said zones, said delay line including a plurality of series connected filaments of semiconductor material and P–N junction portions.

2. A semiconductor device comprising a body of semiconductor material having alternating zones of different conductivity material and a semiconductor delay line contiguous with one of said zones and connected to another one of said other zones and thereby providing feedback between said one zone and said other one of said zones, said delay line including a plurality of series-connected alternating filaments of semiconductor material of one type of conductivity and P–N junction portions.

3. A semiconductor device comprising a body of semiconductor material having alternating zones of different conductivity material and a semiconductor delay line connected to one of said zones, said delay line including a plurality of series connected alternating filaments of semiconductor material of one type of conductivity and P–N junction portions and bias voltage means connected to said P–N junction portions for varying the capacitance thereof.

3,138,743

MINIATURIZED ELECTRONIC CIRCUITS

Jack S. Kilby, Dallas, Tex., assignor to Texas Instruments Incorporated, Dallas, Tex., a corporation of Delaware

Filed Feb. 6, 1959, Ser. No. 791,602

25 Claims. (Cl. 317—101)

It is, therefore, a principal object of this invention to provide a novel miniaturized electronic circuit fabricated from a body of semiconductor material containing a diffused p-n junction wherein all components of the electronic circuit are completely integrated into the body of semiconductor material.

As will be apparent to one skilled in the art, ohmic connections are those which exhibit symmetry and linearity in resistance to flow of current therethrough in any available direction. If two resistors are to be connected together, it is not necessary to provide separate terminations for the common point. The resistance may be calculated from

$$R=\rho L/A$$

where L is the active length in centimeters, A is the cross sectional area, and ρ is the resistivity in ohm-cm. of the semiconductor material.

Capacitor designs may be obtained by utilizing the capacitance of a p-n junction, as shown in FIGURE 2, wherein a semiconductor wafer 15 of p-type conductivity is shown containing an n-type diffused layer 16. Ohmic contacts 17 are made to opposite faces of the wafer 15. The capacitance of a diffused junction is given by

$$C=A\epsilon\left(\frac{qa}{12\epsilon V}\right)^{1/3}$$

where A is the area of the junction in square cm., ϵ is the dielectric constant, q is electronic charge, where a is the impurity density gradient, and V is the applied voltage.

What is claimed is:

1. In an integrated circuit having a plurality of electrical circuit components in a wafer of single-crystal semiconductor material, a plurality of junction transistors defined in the wafer, each transistor including thin layers of semiconductor material of opposite conductivity-types adjacent one major face of the wafer providing a base and an emitter region which overlie a collector region, the base-emitter and base-collector junctions of each of said transistors extending wholly to said one major face, a plurality of thin elongated regions of the wafer exhibiting substantial resistance to provide semiconductor resistors, the elongated regions being spaced on said one major face from the transistors, and conductive means connecting selected ones of the elongated regions to regions of selected ones of the transistors.

2. In a semiconductor device which includes a single-crystal semiconductor wafer: a junction transistor provided adjacent one major face of the wafer by thin layers of semiconductor material of opposite conductivity types overlying one another and extending to said one major face with the emitter-base and base-collector junctions of the transistor extending wholly to said one major face; and a resistor provided in the wafer by a discrete elongated region of the semiconductor material which is spaced from the transistor on said one major face.

3. An integrated circuit comprising a wafer of semiconductor material containing a plurality of electrical circuit components including at least one active circuit component and at least one passive circuit component, the active circuit component including at least two thin layers of semiconductor material of opposite conductivity-types extending to one major face of the wafer with p-n junctions of the active circuit component extending wholly to said one major face, the passive circuit component including at least one discrete region of the semiconductor material of the wafer which is spaced on said one major face away from the thin layers of the active component, substantial electrical impedance being exhibited between the semiconductor material contiguous to the at least one discrete region of the passive component and semiconductor material immediately underlying said thin layers of the active component.

The author of this book would like to offer a different view of the history of microelectronics. My view is based on personal experience as a Diffusion Engineer for almost 40 years. I experienced, unfortunately too many times, that the company establishment was frequently one of the biggest, if not the biggest obstacle, which needed to be overcome in the introduction of new ideas.

This book is my personal story, and my recollection of events may be biased. I am not asking the reader to agree with my statements but I will be delighted if readers will exercise their own judgment. This book is addressed to creative people who think for a living but are not convinced that they already know it all. I met and worked with people I did not like, and I treated them accordingly. I am proud that I was fired by some of them and I consider it as a distinction. On the other hand, I worked with a much bigger group of individuals who made my life extraordinary and many of them became my role models. I regret that I did not save more historical materials, did not ask more questions or did not spend more time with people who were characterized as troublemakers, eccentric, whistleblowers or "difficult persons," and for whom I am using the term "creative individuals". Regretfully, many of them are not with us anymore.

Creative individuals are critical to the success of any innovative process. The common characteristic of creative individuals is their willingness to surmount obstacles and persevere. Any creative endeavor will undoubtedly face obstacles because such endeavors threaten some established or entrenched interest, or status quo.

Research of human behavior consistently reveals a significant difference between creative and uncreative people, and sheds light on why highly creative individuals frequently cause trouble. Creative individuals exhibit atypical thought processes and mental content, they are less constrained by conventional expectations, and they are less concerned with making the right impression on others. Highly creative individuals do not respect common practices. Their methods, style, authoritarian control, and temperament are frequently at odds with conventional norms.

There are also differences in how these two groups process information. Creative individuals have a wider range of attention – they can think of more things at the same time than less creative people. They are also more open to new information and willing to take a higher level of risk. Creative people usually have a very deep knowledge of their subject. This high level of expertise can very frequently lead to problems when the mind becomes "set". Once their mind is set, creative people become persistent and try to overcome any obstacle. The outcome of such activities can result in phenomenal discoveries or colossal failures.

Creative people are introverted, independent, arrogant and hostile. Creative people are over-reactive. Highly creative individuals are usually high-maintenance employees. Creative people are driven with a strong need for achievement and they have the self-belief and energy to challenge the practice of the system and their managers. An engineer usually does not tell his supervisor that he wants to realize his creative potential. Rather he expresses these needs with symptomatic behavior that may become troublesome if the needs remain frustrated. Such behavior may become increasingly disruptive. The highly competitive and ultimately detrimental interaction between strong personalities eventually results in destroying the system, the organization or, more frequently, in the separation of the creative person from the organization and creating a new spin-off or organization. This new organization is set up by rules defined by a creative person that has in the beginning top-notch knowledge of a particular problem. As the business succeeds and expands this originally creative person sometimes becomes preoccupied with business issues and becomes increasingly disconnected from creative scientific work. Unless the founder of a start up is able to adjust to new situations, then gradually, the original dynamic environment will move to the same stagnant environment from which the creative person originally separated. At this time a new generation of creative people will initiate a new cycle of unusual and unconventional thinking.

The transistor and integrated circuit was a result of the creativity of high-maintenance employees. Their creativity was colossal and, therefore, all their behavioral flaws were colossal. This, however, does not make them as a person or their accomplishments smaller.

When I was a younger engineer I was naive enough, not to look back in history. I was always bashing history and art students, who kept their class in the park in shadow of a tree and discussed Nietzsche or Shakespeare. Physics students had to be in laboratories, in front of a blackboard and had to work hard on their experiments. From history I could have learned that really almost nobody cares about the methods of polysilicon doping or channel concentration, but almost everybody cares about the quantity of money or power they have. Certain human behavior has a character of axiom, and will never change. In my naiveté, I assumed that history is something that is part of our past and no changes or editing are needed. I was wrong! To illustrate this statement I will use the example which I faced during the course of writing this book: on November 4, 2003 the CBS issued this Press Release

> *(CBS) CBS Dumps Reagan Miniseries*
> *Mounting pressure and criticism from conservatives has prompted CBS to dump "The Reagans," the network's prime-time miniseries on former President Ronald Reagan. "The Reagans" had been scheduled to air on Nov. 16 and 18. November is a ratings sweeps month of special importance to TV networks since it helps to determine how much they may charge advertisers.*

Criticism of CBS took on an official tone with a letter of complaint from Republican National Committee Chairman Ed Gillespie to CBS President Les Moonves. The New York Times, citing unidentified people close to the production of "The Reagans," reported that CBS executives had previously reviewed the script and viewed the miniseries without raising any objections to the content.

Why were the CBS executives comfortable with the miniseries, and Ed Gillespie was worried? The majority of people in this nation still remember the Reagan era, and they can easily judge if the miniseries is true to history. Obviously, to be in charge of a particular "version of the truth" is of paramount importance. We may think that this is politics, and such things cannot occur in a business environment. There could be few individuals who believe it. The majority of individuals are not that naïve.

The current "politically correct" establishment is aware of problems that creative individuals with independent minds can create so they impose rules defining what is acceptable and what is not. Of course, the threshold between acceptable and unacceptable is defined by "them." When I served in the army, our commander, whose mental ability was on a level suitable for his position, walked in front of the unit, looked into the face of each of us and then puzzled and visibly disappointed, shouted *"This is horrible. Each of you is different!"*

They want us to be the "same," to follow "them," because they know better than we do, what is good for us. If creative individuals cannot be trimmed, they need to be fired, they need to be discredited. And if this is not working, they need to be portrayed in a negative light, for example, as a racist. Of course these are the methods of fascists and communists. I have first hand experience with both of these regimes. Since the time of Plato the problem is that "*There are two kinds of people: Those who do not know, and a much bigger group of those who do not know that they do not know.*" Ed Gillespie knows and he wants that we do not know.

The second example is directly related to the semiconductor industry. In the middle of the sixties several authors published predictions about the future of microelectronics. Gordon Moore of Fairchild published his prediction in Electronics Magazine [1], Jay Last of Amelco presented his view at the Teknorama Conference in February 1967 [2], and Orville R. Baker of Signetics presented his data at the National Electronics Convention [3] the same year. Last provided the source of his data and showed that between 1961 and 1966 the number of transistors increased each year by a factor of 1.6. Baker, based on Fairchild and Signetics data, showed the area in square mils per Flip-Flop circuit. The area decreased by an average of 1600 mils^2/year.

The details of the presentations by Baker and Last are forgotten. The "data" by Gordon Moore, became so-called Moore's Law and the ideology of the Intel Corporation. In the original paper Gordon Moore did not explain what is the definition of "number of components per integrated function." Because Moore included the single transistor data into the plot, the original figure is somewhat confusing. Intel's Public Relations Department apparently decided that transistors are not an "integrated function", and they also believed, for any base the logarithm has a singularity at zero; therefore the

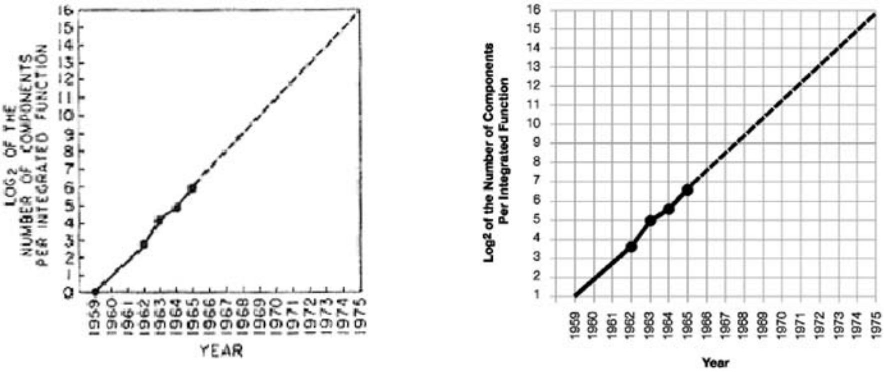


Fig. 4. Original (left) and "fabricated" (right) data defining so-called Moore law. (Original was published in Electronics magazine, April 19, 1965; the fabricated data are from Intel's Press Kit http://www.intel.com/pressroom/kits/events/moores_law_40th)

original plot was modified. In 2005, Intel's Press Kit "Moore's Law 40^{th} Anniversary", Intel decided to create "new data" and pasted it into the original document. Because Moore's paper, contrary to Last and Baker's presentations, did not include real data, nobody really bothered to notice that the data changed the magnitude.

Moore never disclosed the source of his data. Very likely, Fairchild's Micrologic circuits, developed during 1960 and 1964 by R. Norman and R. Anderson (shown in Fig. 5) was used as a base for an observation now called "The Law."

To avoid confusion with altered data, I am trying to support my argumentation with many documents that were not previously published. We all know that human memory fades, especially in the cases of success or failure, and has a tendency to find a way to join the success, and to separate as much as possible from the failure. When success or failure is documented, none or very little memory is needed. Because fewer and fewer libraries keep old publications in their collections, for many people it is difficult to find the real historical facts. And because only a few have access to a corporation's internal documents, it is not surprising that some implanted new and "corrected" information subsequently become "truth."

This book is my personal story and it is story about engineers who refused to be "the same." I do not need to rely on historians' assessments and their research of semiconductor business; I lived this history, I was privileged enough to know many of the key figures described in this book. This claim is not the same as the claim: "I cannot be wrong." Certainly, I may not have the complete information about all events. I am more than happy to modify my statements if new facts are provided. My approach to the possible corrections, however, is the following: *"In God we trust. All others bring data."*

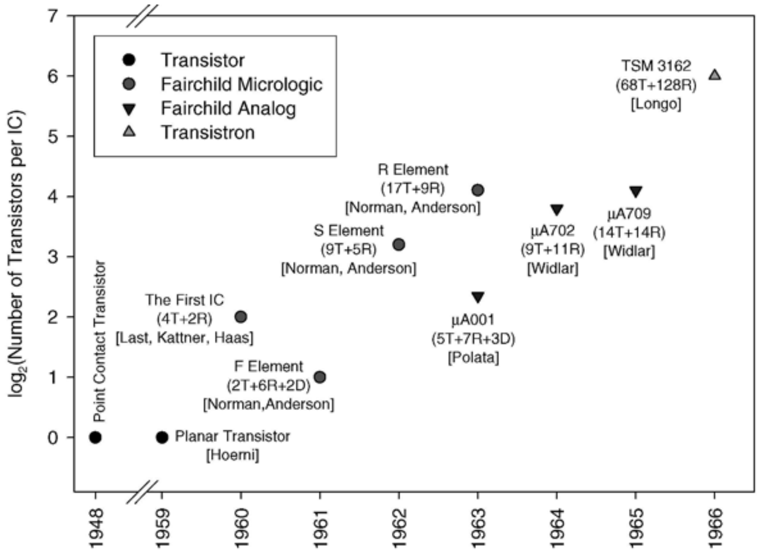


Fig. 5. Very likely source of data G. Moore used in his 1965 Electronics paper (T = Transistors, R = Resistors, D = Diodes)

I am offering a different opinion about several myths and common folklore knowledge of events, which took place almost fifty years ago when semiconductors started to be a business. During the course of this work I was relying mostly on my recollections and life-long interests in the history of semiconductor engineering. I accumulated a significant amount of samples, wafers, photographs and news clippings. I noticed that history is like a solid-state diffusion process that is evolving with time. The state-of-the-art Rapid Thermal Processing of semiconductor reduces the diffusion evolution of dopants to a minimum. Unfortunately, there is no similar process known for the treatment of history.

Historians do not own the past, but they do get to make up the rules as to what counts as history. In post literature society, where fewer and fewer books are read, every new attempt to investigate the past bears increasing responsibilities to be chroniclers of history. The main obstacle is that there is no absolute objectivity in history. You can pick virtually any topic and find twenty, a hundred, or a thousand histories, all of which will be different. I can go down the checklist of all the historical facts, be totally faithful to it – and manipulate the hell out of people through iconography and symbolism. I do not know of a way to be truthful in my book except to be emotionally truthful.

Of course, many of these fictional recreations may or may not be true to history, but my objectives are to present my knowledge and let the reader conclude with his own opinion. You do not censor things. History can put us in relation with the past in a way that tells us something about ourselves.

With this book I want also to pay a tribute to the memory of William B. Shockley. In my entire life I have not met a more creative and resilient person than William B. Shockley. I found between my friends only a few persons who would say a friendly word about Shockley. Shockley was very complex, difficult and extraordinary in many ways. He was a brilliant physicist who could not pretend anything. His social skills were close to none. If you were stupid he would tell you and it would not be wrapped in politically correct nonsense.

Niccolo Machiavelli wrote in "The Prince": *The Innovator makes enemies of all those who prospered under the old order, and only lukewarm support is forthcoming from those who would prosper under the new.* Shockley made many of his enemies because in ten cases he was right nine times. A majority of people, do not appreciate when someone constantly demonstrates that he is sharper.

Interestingly enough, the majority of those who sharply criticize Shockley never forget to put into their resumes or biographies a note that they worked with and were trained by Bill Shockley.

Shockley created not only Silicon Valley and a new industry, but he changed the way we live. If the atomic bomb had not been invented, or if we did not reach the Moon, the life of the majority of people would not be affected. However, I cannot imagine my life without the transistor, even though I do not use a mobile phone.

The fundamental theory of the PN junction as used today was formulated by Shockley in a very short period of time. Shockley became the most respected man by many at the age of forty. There was, and still is a bigger group of others who envy him. What was the source of his genius or what some call evil genius? My answer is that Shockley was a man that Nature rarely produces and who only appears on Earth at intervals of centuries.

It is too sad that Shockley never shared in the rewards that so many Silicon Valley pioneers have reaped.

References

[1] G. E. Moore, "Cramming more components onto integrated circuits," Electronics, Vol. 38 (1965), April 15

[2] J. Last, Presentation at Teknorama Conference, Stockholm, February 1967, (published as "Integrerad elektronisk kretsteknik av idag", Elektronik, Vol. 4 (1967), p. 40

[3] O. R. Baker, "Aspects of Large Scale Integration," NEC Record 1967, p. 56

1

Research Organization: Bell Telephone Laboratories

> *"Our species is the only creative species, and it has only one creative instrument, the individual mind and spirit of man. There are no good collaborations, whether in music, in poetry, in mathematics, in philosophy. Once the miracle of creation has taken place, the group can build and extend it, but the group never invents anything. The preciousness lies in the lonely mind of man."*
>
> *John Steinbeck, East of Eden*

Bell Laboratories were jointly owned by the American Telephone & Telegraph Company and Western Electric, AT&T's production subsidiary. At the end of World War II the Laboratories employed about 11,000 people, of whom about one-third were professional scientist and engineers, about one-third technical aides, and about one-third clerical and support personnel. Approximately 85 percent of the laboratory staff was engaged in the development of specific devices and systems for use in telephone systems or by the military. About 15 percent of the professional staff under the Vice-President of Research, William O. Baker, was involved in research which was not related to any specific objective.

During World War II, Bell Laboratories undertook more than 2000 research projects for the Army, Navy, and the National Defense Research Council. Between 1949–1959, the U.S. Government funded more than $600 million of research at Western Electric and Bell Laboratories (approximately 50% of total Research Budget of Bell Laboratories.) During this period the Department of Defense allocated between $1 million and $2 million annually to over one hundred doctoral candidates working on basic research of solid-state physics. Support of scientific research began to pay important dividends very quickly.

The idea to develop a solid-state switching device originate from Bell Laboratories' brilliant Director of Research, Mervin J. Kelly. Kelly was very exceptional, extraordinarily keen, alert and practical. Visionary Kelly was motivated by a desire to replace mechanical relays in telephone exchanges with solid state devices.

On November 2, 1956 when William B. Shockley won the Nobel Prize and responded to Kelly's congratulation, Shockley wrote:

> *"Dear Mervin, It is hard for me to see as a research director and vice president in your position could have proceeded more effectively to get a transistor out of a solid state physicist like myself. The background of experience I had in the vacuum tube area and some talks you once gave me on the importance of electronic switching stimulated me to be alert to such possibilities. This was then followed by the freedom to work on subjects of my own choosing in the solid state physics area. I hope that we shall have an opportunity to pat each other on the back over a drink before too long."*

Shockley obtained his doctorate from MIT in 1936 where he became the protégé of Prof. P. M. Morse. His doctoral thesis was entitled "Calculations of wave functions for electrons in Sodium Chloride crystals" and was supervised by Professor John C. Slater. Shockley turned down several offers (General Electric, Yale University) and joined Bell Laboratories because he wanted to work with C. J. Davisson (who later won a Nobel Prize for his work on electron diffraction). Shockley was assigned to the Vacuum Tube Department previously headed by Mervin J. Kelly.

When Kelly became the research director of Bell Laboratories he put William Shockley in charge of the Solid State project. Shockley first considered materials which were investigated earlier by the Pohl group in Germany, and Davydov and Joffe in Russia and which was reasonably well understood, Copper Oxide, for example. Shockley envisioned a device (Fig. 1.1) which later failed to behave as predicted by theory. However, the experience learned during the course of this work firmly established motivation and desires to pursue the idea.

The research work was interrupted by World War II. In 1940 Shockley worked on the J. B. Fisk project "Uranium as a source of power." In 1942 Shockley left for assignment to the newly established Office of Scientific Research and Development (OSRD.) This was headed by MIT engineer and legend Vannevar Bush with James B. Connant, a chemist and president of Harvard University and other prestigious members of the scientific community. OSRD was a federally-funded civilian organization with the main goal to coordinate the war effort between the science community, business and the government.

12/29/39 4:15 PM

Friday, I home in Gillette

A semi conductor triode or amplifier

It has today occurred to me that an amplifier using semi conductors rather than vacuum is in principle possible. Suppose, for example, that a very fine mesh copper screen is oxidized thus giving a metal grid imbedded in oxide and let the ohmic contacts be made to the outer surfaces. Then if the carriers of charge are for convenience regarded as positive, if the grid is made plus, a space charge sheath with carrier deficit forms around it. This gives a region of low conductivity and accounts for high resistance in the reverse direction for the rectifying junction. Suppose the region is so large that it envelops the entire system of grid wires. Next suppose that an additional neg. potential is applied to the right hand ohmic contact. This draws some, but not many more carriers from the grid and few if any from the left electrode because the grid wires are surrounded by the negative sheath which fills the space between

12/29/39 cont. ②

them. If on the other hand the grid is at zero; then make right positive draws current, much as if grid were not there, from the left. We can say that the grid effectively can be used to raise the resistance in its vicinity and thereby hinder the flow of current from left to right. Since the grid is being used in the reverse direction, its resistance is high and it will not consume much power, whereas relatively large currents flowing from left to right can be controlled.

Another modification would be to use a very small oxidized wire. Making the wire positive will increase the resistance between the two contacts without consuming much "grid current".

12/29/39 W. Shockley

Read – understood Feb 27 1940
J.A. Becker

Fig. 1.1. Copper Oxide Solid State Amplifier envisioned by W. Shockley on December 29, 1939, Bell Telephone Laboratories Notebook # 17006 assigned to William Shockley (Dept. 328-3), September 1, 1939

Under the direction of V. Bush, Shockley become Director of Research of the Antisubmarine Warfare Operations Research Group[1] and in 1944 he became an Expert Consultant in The Office of the Secretary of War working on deployment of radar in the B-29 program.

The small group at Bell Laboratories continued solid state research under the direction of MIT Radiation Laboratory to purify the semiconductor material for microwave detector used in radar. Russell Shoemaker Ohl (1898–1987) who was trained in electrochemistry and a graduate of Penn State in 1918, discovered during the course of investigations of the properties of crystal detectors for radar, the first p-n junction device when he accidentally cut a section of sample across an (invisible) boundary between p and n regions of a silicon ingot solidifying from a doped melt.

On March 6, 1940 Ohl showed his sample to Mervin Kelly. Kelly called Walter Brattain and Joseph Becker. Brattain immediately suggested that the

[1] Shockley actually invented and coined the phrase "*Operations Research*" during his work on antisubmarine warfare

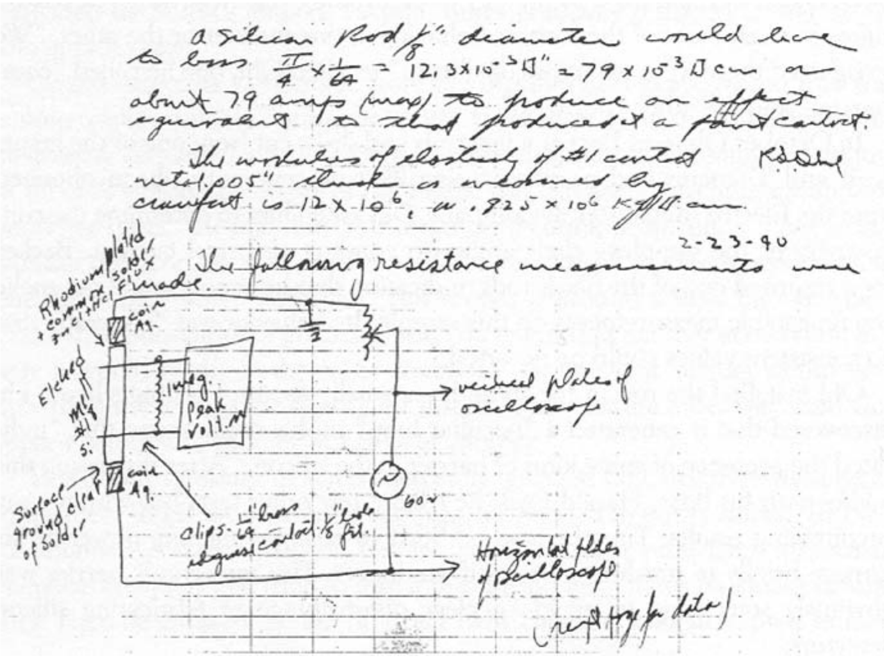


Fig. 1.2. Circuit used by R. Ohl to measure the resistance of a silicon rod. The unusual behavior of the current passing through the sample let to the discovery of the P-N Junction. [R. S. Ohl Laboratory Notebook, February 23, 1940]

electrical current must be due to "some barrier being formed in the crystal" and nothing else happened.

Mervin J. Kelly in the spring of 1945 was promoted to vice-president in charge of research. He immediately, in June 1945, organized goal-oriented research and signed the Authorization for Work requesting "*new knowledge that can be used in the development of completely new and improved components.*" (Fig. 1.3.) Kelly established several new research groups. William Shockley and physical chemist Stanley Morgan headed Solid State Physics Department. Physical chemist Addison H. White was in charge of Electronic Materials Department, and Jack A. Morton directed Basic Research. Shockley was still heavily involved in military projects (Policy Council Joint Research) and often in Washington D.C.; S. Morgan substituted as group leader during Shockley's absence.

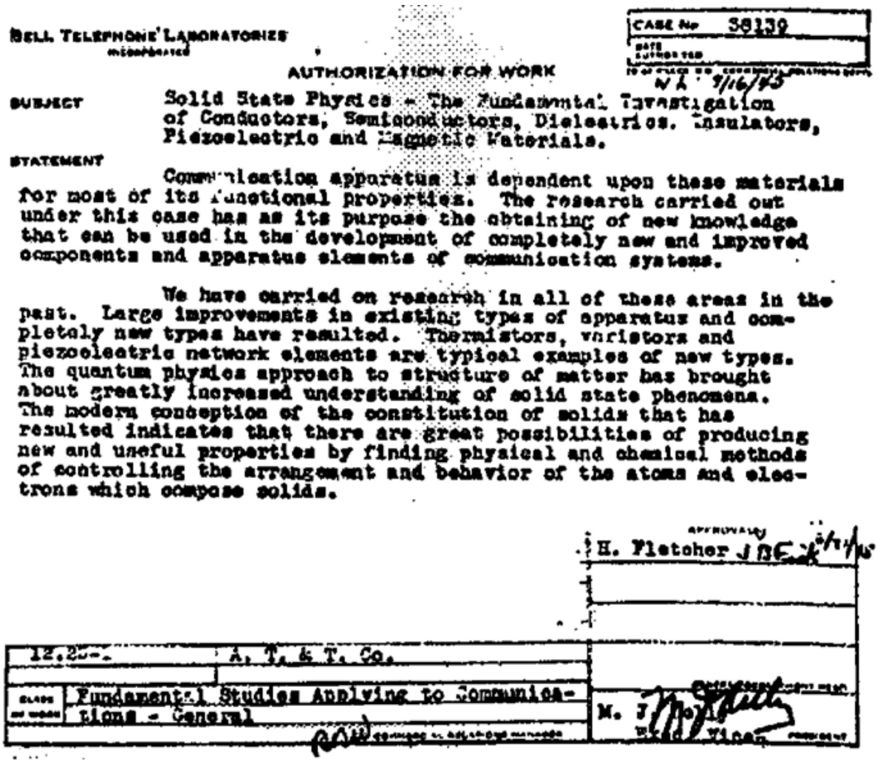
The department originally included experimentalist Walter Brattain, John Bardeen, a theoretician who joined Bell Laboratories from the Naval Ordnance Laboratory in late 1945, experimentalist Gerald Pearson, physical chemist Robert Gibney, and electrical engineer Hilbert R. Moore.

Shockley and Morgan's Solid-State Department, reported to Harvey Fletcher, the Director of Physical Research. Fletcher reported to Ralph Bown, the Director of Research.

President Harry Truman honored Shockley with a Medal of Merit on July 19, 1946 with the citation *"By his tireless efforts, initiative and skilful application of scientific techniques to the problems confronting the army, he made an exceptional contribution to the war effort."*

On September 6, 1945 Shockley and Morgan visited Karl Lark-Horovitz group at Purdue University. Prof. Lark-Horovitz with small group of students and scientists (V. A. Johnson, S. Benzer, R. Bray, R. E. Davis, L. G. Dowell and W. W. Scanlon) conducted since March 1942 research funded by OSRD on "Preparation of Semi-Conductors and Development of Crystal Rectifiers." Based on the work of Purdue group Shockley reach very important conclusion – the only semiconductor materials at that time with good prospect, were elemental Germanium and Silicon.

In January 1946, Shockley predicted, based on the existing theories for Germanium and Silicon, that a significant modulation of conductivity of thin layers of semiconductor should be produced by inducing a surface charge by strong electric field. The proposed form of modulation became known as



BELL TELEPHONE LABORATORIES
INCORPORATED

CASE No 38139

AUTHORIZATION FOR WORK

SUBJECT Solid State Physics - The Fundamental Investigation of Conductors, Semiconductors, Dielectrics, Insulators, Piezoelectric and Magnetic Materials.

STATEMENT

Communication apparatus is dependent upon these materials for most of its functional properties. The research carried out under this case has as its purpose the obtaining of new knowledge that can be used in the development of completely new and improved components and apparatus elements of communication systems.

We have carried on research in all of these areas in the past. Large improvements in existing types of apparatus and completely new types have resulted. Thermistors, varistors and piezoelectric network elements are typical examples of new types. The quantum physics approach to structure of matter has brought about greatly increased understanding of solid state phenomena. The modern conception of the constitution of solids that has resulted indicates that there are great possibilities of producing new and useful properties by finding physical and chemical methods of controlling the arrangement and behavior of the atoms and electrons which compose solids.

H. Fletcher

A. T. & T. Co.

Fundamental Studies Applying to Communications - General

M. J. Kelly

Fig. 1.3. Authorization for Work to begin Solid State Physics research in Bell Laboratories signed by Mervin Kelly in June 1945.

the “field effect.” Realizing the practical implication of such a possibility, Shockley proposed experiments to test his hypothesis.

A number of experiments were carried out by J. R. Haynes, H. J. McSkimin, W. A. Yager and R. S. Ohl. However, the degree of modulation had been considerably less than predicted by theory. Those results lead to a re-examination of the theory and the postulation of surface states by John Bardeen. Bardeen’s idea resulted in additional speculation about the presence of a space charge region that may exist at the surface of a semiconductor. According to Pearson and Brattain [1], having postulated a space charge region at the free surface of a semiconductor, the question arose how to verify experimentally its existence. W. Shockley pointed out that “according to this picture the contact potential between n and p type samples should increase with doping.” Experiments performed by Pearson and Brattain proved that this was the case.

In the fall of 1947 Brattain and Gibney experimentally studied properties of Bardeen’s surface states. There was little or no theory explaining the unusual experimental behavior observed on measured samples. In November 1947, R. B. Gibney made a key suggestion which influenced all future experiments. Gibney suggested that voltage be applied between the metal plate and semiconductor (Fig. 1.4.) Gibney proposed a structure of semiconductor with contact at the periphery, and with a second contact in the center of the structure formed by electrolyte. When these connections were made, a current flowed through the sample and its magnitude was mainly determined by sample resistivity. When the potential of the electrolyte was modulated the current in the external circuit was accordingly modulated.

Brattain and Gibney had overcome the blocking effect of the surface states – the practical problem that had caused the failure of the original “field effect” experiment. They proposed amplifiers using the field effect with electrolyte to obtain the desired high electric field.

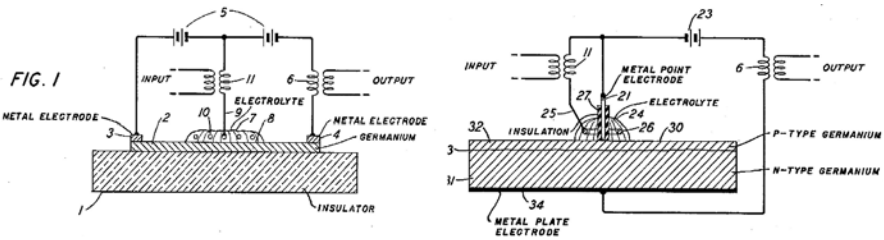


Fig. 1.4. A drawing from the Brattain and Gibney patent application experimentally verified on November 20, 1947 [U.S. Patent 2,524,034].

On November 23, 1947 (Sunday) Bardeen referred to observations by Brattain and Gibney and suggested a modified structure (Fig. 1.5) where liquid

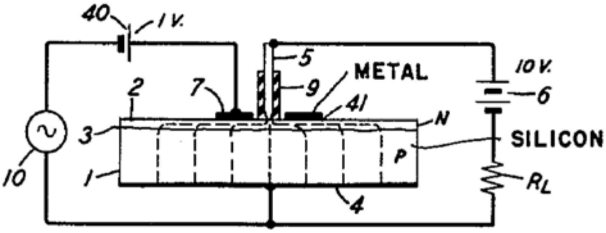


Fig. 1.5. Bardeen's disclosure of "Three-Electrode Circuit Element Utilizing Semiconductor Materials" dated November 23, 1947 [U.S. Patent 2, 524,033]

electrolyte was replaced with metal forming a rectifying contact with semiconductor. The suggestion become U.S. Patent 2,524,033 where Bardeen wrote:

> *"the current, in making its way through the block from the source electrode to the collector, first spreads out laterally in the surface layer in all directions from the source electrode before crossing the barrier. In accordance with the invention in one of its aspects, a third electrode, denoted the control electrode, is disposed to exert its influence on this spreading resistance.*
>
> *The result is a substantial modification of a substantial part of the whole internal resistance of the device, and so a substantial alteration of the current in the external circuit."*

Bardeen's patent application referred to Gibney's previous work which later became U.S. Patent 2, 560,792 where Gibney suggested the structure which leads to transistor version as demonstrated in December 23, 1947. Gibney wrote:

> *"thin surface layer of P-type material containing fixed negative charges and mobile positive charges, and high resistance barrier which separates this thin surface layer from the main body of the block which has N-type characteristics containing fixed positive charges and mobile negative charges.*
>
> *Positively biased metallic electrode placed on the P-type surface layer serves as emitter and positive charges "holes" tend to flow away from the emitter electrode in all direction before crossing the barrier. Some of them flow in the neighborhood of the negatively biased electrode which may be termed collector.*
>
> *Evidently the portion of the emitter current which is collected by the collector depends on the distance which separates these two electrodes."*

Brattain's notebook from December 8, 1947 reports a very important change. The Gibney device (Fig. 1.4) with the drop of electrolyte and the point-contact structure exhibited voltage and power gain; however, the device had a new feature: so-called "high back voltage" N-type germanium. "High back voltage" germanium is high resistivity material – a central feature necessary for achieving the voltage gain of the point contact transistor. Brattain's entry also contained a note about a luncheon discussion with Shockley and Bardeen where Bardeen suggested use "high back voltage" germanium studied by Lark-Horovitz group at Purdue. The reasoning behind this suggestion was to get a better rectifying contact of high resistivity material in comparison with low-resistivity silicon or germanium samples they used before.

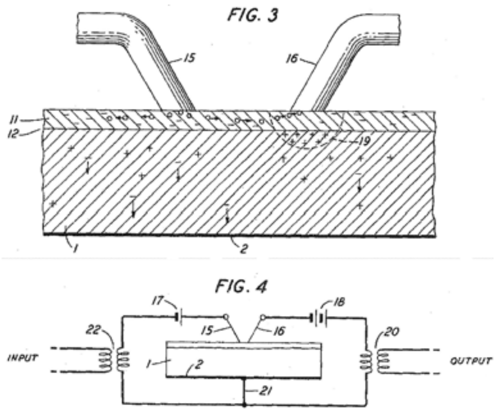


Fig. 1.6. Gibney patent # 2,560,792 which for the first time introduced terms "Emitter" and "Collector"

Then Brattain, sometime before December 16, 1947, got a brilliant idea to apply gold on a wedge and then separate the gold at the point of the wedge with a razor blade to make two closely spaced contacts as shown in Fig. 1.7. Twenty years later Brattain in interview for IEEE Spectrum magazine recalled his experiment: *"I accomplished it by getting my technical aide to cut me a polystyrene triangle which had a smart, narrow, flat edge and I cemented a piece of gold foil on it. After I got the gold on the triangle, very firmly, and dried, and we made contact to both ends of the gold, I took a razor and very carefully cut the gold in two at the apex of the triangle. I could tell when I had separated the gold. That's all I did. I cut carefully with the razor until the circuit opened and put it on a spring and put it down on the same piece of germanium that had been anodized but standing around the room now pretty near a week probably. I found that if I wiggled it just right so that I had contact with both ends of the gold that I could make one contact an emitter and the other a collector, and that I had an amplifier with the order of magnitude of 100 amplification*[2]*, clear up to the audio range."*

[2] Human memory is imperfect, and later accounts are often subject to "Retrospective Realism." Documented amplification of the Brattain device, during tests performed on December 16, 1947, had a voltage gain of fifteen.

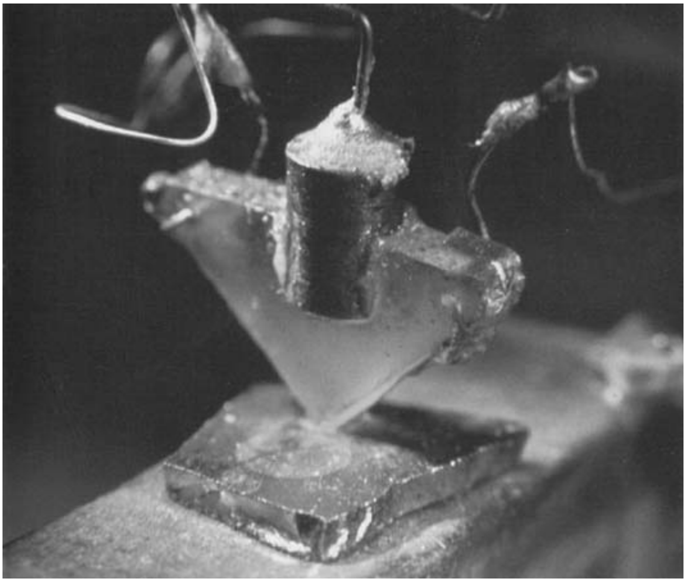


Fig. 1.7. The triangular wedge is made of plastic and is covered with gold foil slit in half at wedge's tip. One side of the wedge serves as the emitter, the other as the collector. The piece of germanium acts as the base. Actual size of the wedge is approximately 30 mm

The wedge assembly was completed on December 16, 1947 and the testing was completed that same afternoon. The transistor was born.

On the afternoon of December 23, 1947 H. R. Moore connected the input of the transistor to a 1 kHz signal and the output to an oscilloscope. R. B. Gibney, J. Bardeen, G. L. Pearson, W. Shockley, W. Brattain, H. Fletcher and R. Bown witnessed the test (Fig. 1.8 and 1.9.) The power gain was 1.3 and the voltage gain fifteen. The next morning, on December 24, 1947 Brattain and Moore demonstrated to M. Kelly, Bell Laboratories Vice-President, Harvey Fletcher, the Director of Physical Research, and Ralph Bown, the Director of research, device operating as an oscillator.

Bell Laboratories immediately declared the invention as "BTL Confidential" and added more people to "Surface States Project," Among them were John Shive, Jack Scaff, William Pfann, and J. A. Becker. Bell Laboratories filed five patents in February 26, 1948 covering the basic principle of the transistor. Gibney's name appears on two patent applications. Although his contribution was crucial to the discovery of the transistor, his name disappeared from history.

Gibney was born in Wilmington, DE on August 30, 1911. His undergraduate degree was in Metallurgy from the University of Delaware, and his Ph.D. was in Physical Chemistry from Northwestern University. He began working at Bell Labs right out of graduate school in 1936. He worked in the chemistry

Inventors	Case No.
John Bardeen - Walter H. Brattain	3-9

Conception of Any Complete Form of Invention

1. Date. (Approximately if unable to fix exactly.)	1 December 15, 1947
2. Circumstances attending conception	2 Investigation of effects of electric fields on surfaces of semiconductors

Drawings Showing Features of Invention

3. Nature of drawing? (Pencil sketch, marked blueprint, etc.)	3 Pen and ink drawing
4. Date and by whom could the date be proved?	4 December 19, 1947
5. Where filed?	5 Notebook 21780, page 6
6. Subsequent drawings, if any?	6 Notebook 20780, page 71

Disclosure
(Explanation of Invention Made to Another)

7. To whom? Written or oral?	7 W. Shockley, H. R. Moore - oral
8. Date?	8 December 16, 1947
9. If recorded, where?	9 Not recorded

Written Description

10. What was it? (Memorandum, "circuit description", notes on a drawing, etc.)	10 Circuit description
11. Date?	11 December 16, 1947
12. Where is original filed?	12 Notebook 18194, page 192

Reduction to Practice
(Physical Embodiment Constructed and Tested)

13. What was constructed?	13 Voice frequency amplifier
14. How tested?	14 Talking over circuit
15. Did it operate successfully?	15 Yes
16. Who constructed it and date?	16 W. H. Brattain, H. R. Moore, December 23, 1947
17. Who witnessed test and date?	17 R. Bown, H. Fletcher, W. Shockley, G. L. Pearson, December 23, 1947
18. Where recorded?	18 Notebook 21780, pages 7,8
19. Is the original model or circuit preserved? If so, where?	19 Yes. Room 1E455 Murray Hill
20. Subsequent tests, if any?	20 December 29, 1947-1E355 and later.

Fig. 1.8. Bell Telephone Laboratories *History of Invention* as recorded by H. C. Hart [HCH:EM 6-4-48]