Chapter 1

Introduction

The story of the invention of integrated circuits (ICs) is like a mystery novel. Instead of waiting until the conclusion of this book to find out "Who done it? Did the butler do it?", a style commonly used by fiction writers of mystery novels, the readers will be surprised with the facts given even briefly in this introduction. I hope to make the readers curious in the very beginning to ask, "How could this have happened? Why nobody questioned it all along?" This should help the readers to have an inquisitive frame of mind about the mystery of invention of ICs. The mystery lies in why many facts of the invention were either ignored or twisted by the powers to be? Further, why did they succeed to mislead and convince the entire community of technologists and scientists in the world, even the patent experts of the US Patent and Trademark Office (USPTO) that the inventors invented what they actually did not, and that the inventors had used the others' inventions to make theirs possible without acknowledging them? Why did even the Nobel Committee, which was responsible for choosing a co-winner of the Nobel Prize in Physics in 2000, accepted an invention which never was, and published his citation which was vague and inconsistent with the purported Nobel award? Why was he awarded 1/2 of the Nobel prize money, and the other two co-winners were given 1/4 each?

Additional facts are that why not any of those who have achieved high fame and made huge fortunes unparalleled in the history of business ever in the whole world, have spoken up, published and corrected the mistakes in the articles in popular and technical literature and patent claims of the IC inventions? A few are donating their fortune to give back to the society graciously and generously, the others are not. The readers are privy to read about both types of such individuals in the popular literature. Many of them were intimately involved from the very beginning in various aspects of the greatest invention of mankind even before the inventions actually took place. On ethical and moral grounds as well as professionally, if anybody who had the plenipotentiary strength to uphold the truth without the fear of jeopardizing their careers and jobs, would have been these select group of people. Why did they remain silent all along? Too busy amassing fame and fortune and soaring ever higher even though the fundamental facts of the IC inventions were on cloudy grounds? Maybe or maybe not; debatable? Sounds mysterious? Yes, it sure does. Is it all fiction? No, the mystery of the invention of ICs is based on well documented facts given in this book which nobody can deny. They are all available as public records.

I shall summarize some of the facts and key information of the invention of ICs in this Introduction Chapter over and beyond those capsulized already in the Preface. Their details have been given in the subsequent chapters. They are also repeated in several portions of the book for the convenience of the readers. This presentation style has been followed not only for the sake of continuity of the discussions in those places, but also to help the readers to avoid going back and forth while reading the book, a popular style also followed by many biography authors of the titans of the 20th century scientists and engineers.

At the outset, I wish to let all the readers know that I have had the highest regard for both late Jack Kilby and late Bob Noyce. I had known Bob Noyce both professionally and personally for about 30 years before he died from a heart attack in 1990. I had also known Jack Kilby professionally for several years, although we had met only a few times in person before he died in 2005. In my opinion, as it is also generally known, both men did make important contributions to the invention of ICs and to the field of microelectronics, and they were very caring and decent human beings too. Therefore any critique that I shall present in this book about their work, is only to uphold the truth of the science and engineering facts, with no disrespect whatsoever to them. My main aim and the only purpose in writing this book is to get the history right based on science and engineering facts, by putting all the available facts on record. I am doing this for the benefit of mankind, especially the younger generations who must be taught the facts to inspire them to achieve their own highest level of attainments in their professional and personal lives.

1. What is an IC?

Why the invention of IC is so important has been given already in Section 2 of Preface. Before getting mired into the details of the inventions of IC by Kilby and Noyce, it will be helpful for the readers who may not be familiar with the IC, to know at the outset what is an IC? This has been capsulized in Section 3 of Preface, but I shall explain it a bit more and its development here.

An IC is a circuit consisting of various active (transistors) and passive (resistors and capacitors, and recently, inductors) devices interconnected by single or multilevel metallizations on a piece of single crystal silicon (Si). It is referred to as a chip in popular language. The only kind of ICs sold widely from the very beginning have been the monolithic-ICs made from Si. We shall exclude in our defintion and in this book the hybrid ICs in every cell phone and other microwave ICs that contain several monolithic Si ICs and transistor chips made on compound semiconductors. Therefore throughout this book, the full expression monolithic-ICs or just ICs shall be used interchangeably; the former will be expressly used when the monolithic aspect is to be emphasized. The details of what are monolithic-ICs, how do they differ from the hybrid-ICs, how did they evolve from the earlier electronic circuits using vacuum tubes, shall be given in subsequent Chapters 3 and 4. Also, what did actually Kilby, Noyce and the others contribute to the invention of ICs shall be given in Chapters 7–9.

The fast evolution of the ICs since their invention in 1959 to the current Ultra Large Scale ICs (ULSICs) is described in Section 5 of Chapter 3. The ICs sold for the first time in 1960 had only a few devices per chip fabricated with minimum geometries measured in mils (1 mil = 1/1000 inch, or one thousandth of an inch), and they were interconnected by a single level of metalization. Now a typical ULSIC has a few billion devices per chip fabricated with minimum geometries measured in nanometers (nm), and interconnected by 8 or more levels of metalizations. To give you an idea of the minimum geometries involved, 1 mil = 25.4 microns or μm; 1 μm = 1000 nm; 1 nm = 10 Å (Angstrom); atomic diameter = 1 to 4 Å; diameter of average human hair = 50 to 100 μm. Advancements in several multidisciplinary technologies have been made to enable large volume production of ULSICs with minimum geometries of 45 nm and decreasing. Comments on Moore's Law which has predicted remarkably well the decrease in minimum geometries and increase of devices per chip for the past 40 years, and how long into the future the densities and complexities of the ICs shall continue to increase, are discussed in Chapters 13 and 14.

2. Key Requirements for making the IC and did Kilby and Noyce meet them?

Before getting mired into the details of the inventions of Kilby and Noyce, it will be helpful for the readers to know at the outset of this Introduction chapter, that the only kind of ICs sold from the beginning have been the monolithic-ICs fabricated and manufactured in large volume on single-crystal silicon (Si), except the hybrid microwave IC's containing several Silicon monolithic ICs and Compound semiconductor IC's which are excluded in this book to focus on monolithic Si ICs. The precise definition of the word "monolithic" will be given in Chapter 4. Although it is not easy to coalesce all the information in one-sentence, the definition of monolithic-IC can be given as:

"All the devices (transistors, resistors, capacitors, inductors) required for the IC, and their electrical interconnecting conductor lines deposited and etched in narrow lines adherent to the selected regions of the devices and insulator (e.g., silicon-di-oxide) surfaces, must be fabricated on a single crystal silicon chip as an integral solid unit which is protected from the influences of the ambient."

It is a mouthful to define in one sentence. But perhaps it may be a reasonable start for a lay-person to visualize that a monolithic-IC is a small piece of silicon with all the circuitry which if tossed around, neither the devices nor the interconnecting lines fall off the chip. They are all adherent to and embedded in the chip. Throughout this book, the full expression monolithic-ICs or just ICs shall be used interchangeably; the word monolithic will be expressly used when the monolithic aspect is to

Table 1.1. Key requirements for making the monolithic-IC and whether or not they were met by Kilby and Noyce in their respective inventions.

Key requirements for making the IC (Four key parts of the requirements)	Kilby	Noyce
1. All devices must be fabricated in the same substrate (e.g., single-crystal Ge, Si).	Yes	Yes
2. Planar technology must be used to fabricate the above devices. (planar; Si)	No (mesa; Ge)	Yes (planar; Si)
3. All devices must be isolated from one another by an appropriate planar technology (e.g., p-n junction, LOCOS, trench).	No (mesa)	Yes (p-n junction)
4. All devices must be connected by planar interconnections adherent to oxide surface.	No (Gold wire bonds)	Yes (Aluminum)

be emphasized. The details of what are monolithic-ICs, how do they differ from the hybrid-ICs, how did they evolve from the earlier electronic circuits using vacuum tubes shall be given in Chapters 3 and 4. However, it will be helpful for the readers to have a global view of the IC inventions of Kilby and Noyce before perusing through the rest of the book. Therefore I shall first summarize the key requirements for making the IC, i.e., monolithic-IC on Si, in Table 1.1, and answer in this table the questions on whether or not they were met by Kilby[1] and Noyce[2] in their respective inventions and patent claims.

In their respective IC inventions as shown in Table 1.1, Kilby met only 1 out of 4 criteria, whereas Noyce met all the 4 criteria. Therefore, Noyce's invention was for the monolithic-IC, and Kilby's invention was not; it was for the hybrid-IC. Hybrid-ICs indeed are still used today in microwave-ICs (such as those in the cell phones), using evaporated metal films adherent to insulator substrates, but not like Kilby's initial reduction to practice in 1958 shown in Figure 1.1. In this figure, wire bonded interconnects can be seen clearly going from one device to another. Figure 1.2 shows the reduction to practice of Noyce's invention of IC. Planar interconnects can be seen clearly between the devices of the monolithic-IC.

For a detailed listing and discussions of the various criteria and documented facts on the monlithic-IC versus the hybrid-IC, see Reference 12 and Chapter 4 of this book.

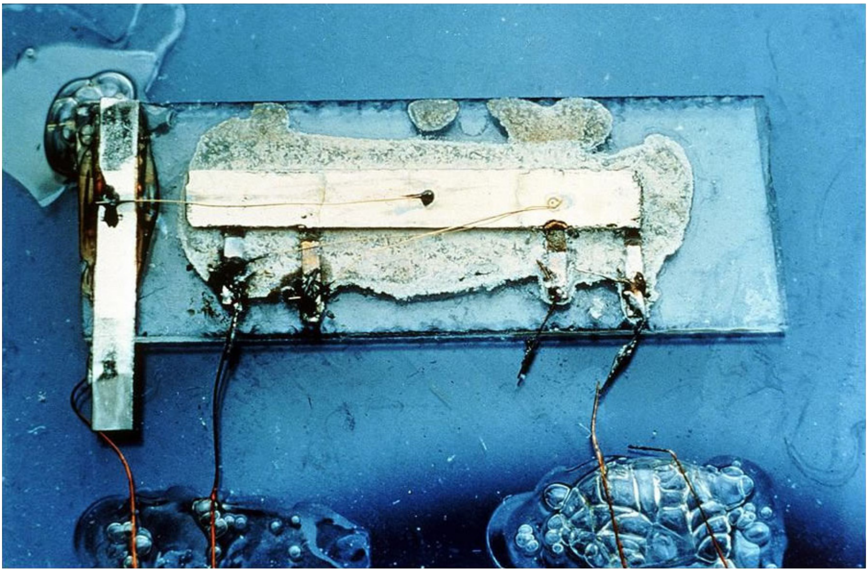

Fig. 1.1. Kilby's reduction to practice of his invention of IC.

3. Sole credit to Kilby and Noyce

The sole credit for the invention of ICs has been given to Kilby[1] and Noyce[2] in the literature since their inventions were disclosed in their respective patent filings in the USPTO ~50 years ago in 1959. Unfortunately this recognition accorded to Kilby and Noyce is only partly correct and justified, and most if not all of the authors and hence the readers on this subject have failed to appreciate this fact. Kilby and Noyce did play key roles in the invention of ICs, but not quite the way they have been portrayed in the literature so far. They have been singled out as if they did it all by themselves in inventing the ICs. They have been given an iconic stature by the hero worshippers without knowing where the credits are actually due and for what?

Also, hundreds of million dollars and some in the billions have been made as profits in their pockets by some of the contributors as well as non-contributors to the IC technology and related businesses, and by those business savvy wizards who happened to be at the right place, at the right time and with the right people. As a professional courtesy and propriety,

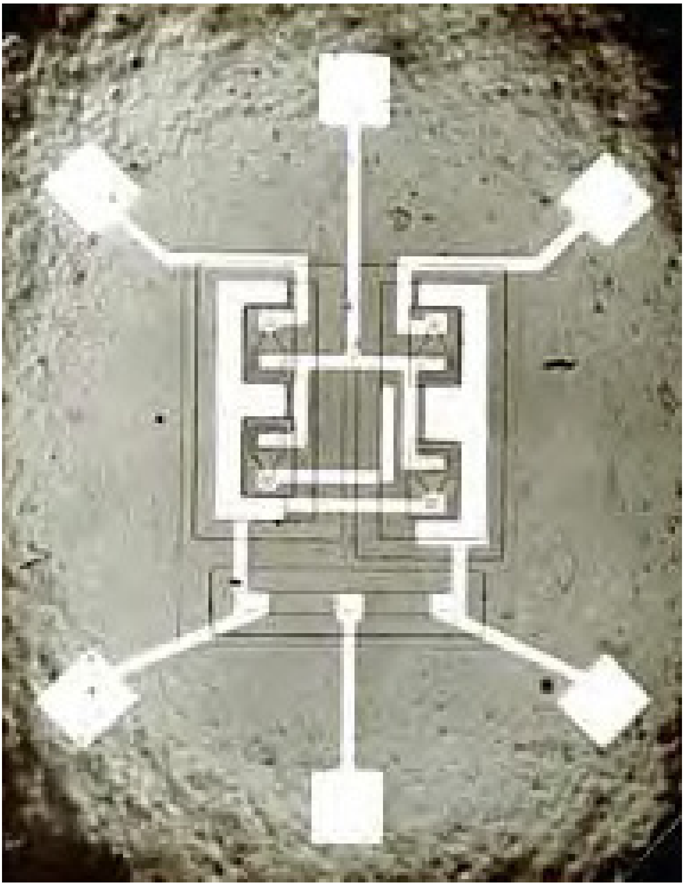

Fig. 1.2. Reduction to practice of Noyce's invention of IC.

I shall not mention the names of several of them whom I knew personally. This is also to avoid the appearance of a conflict of purpose by implication. My sole purpose is to help straighten out the true IC invention history. My presentations in this book are based on my own exhaustive research of the published literature and my own educational science and engineering backgrounds and job experiences (see Appendix 1).

Only a very select few genuine contributors numbering less than the number of fingers on one hand, who have amassed huge fortunes, are giving back to the industry and the society. They are the very admirable few indeed who were lucky, smart and courageous too. Nevertheless, while they and the others have had dame luck smile on them, many other genuine contributors have been ignored by the society; not only by the laymen but also by their technological peers of the latter days including today. Moreover, some of the fundamental facts of the IC invention have either been overlooked or not understood at all by the previous authors on the history of IC. These facts have also been documented in this book. While not taking away the key contributions of Kilby and Noyce, these facts tell a different story about their actual contributions. The details can be found in the subsequent chapters of the book, but a few are summarized below to point out the mystery of the invention of ICs.

4. A few facts in the mystery of the invention of ICs

4.1. One fact is that Kilby did make a key contribution to the invention of ICs by disclosing that all the devices can be fabricated in a single piece of semiconductor. (See Jack Kilby, Fig. 1 in Wolff[3]: "A page from Jack Kilby's notebook of July 24, 1958, where he first recorded how resistors, capacitors, and transistors could be made on a single slice of silicon." As it is clear from this Fig. 1, Kilby's handwritten disclosure was not witnessed, as required by the Patent Law.) But this is only a small part of the complete information needed to make the monolithic-IC. Did he borrow this idea from and limited to the same technical constraints as Geoffrey Dummer[4] in England, who had described the same key yet limited concepts earlier? This remains as yet an unresolved mystery. However the fact also is that Dummer's publication (see Chapter 9) pre-dates Kilby's disclosure handwritten in his notebook. It is also well known that Kilby had attended Dummer's presentation of his paper in 1952 in Washington, DC. Essentially similar suggestions had also been made earlier than Kilby by Harwick Johnson[5] of RCA and Richard Stewart[6] also of Texas Instruments (as Kilby was also from TI but had joined TI later than Stewart).

4.2. Another important fact is that Kilby did not invent the silicon monolithic-ICs, the only kind sold from the beginning to this day (except the hybrid microwave ICs such as those in the cell phones). This fact has been confirmed by a member of the Nobel Committee (Dr. MNC-1) in his written communications with me recently (see Chapter 12). In the specifications of his invention, Kilby did not give the correct procedures for fabricating the devices and their electrical isolation. Moreover he missed completely giving the correct procedures to interconnect the devices (rectifying diodes, amplifying and switching transistors, resistors, and capacitors) in the chip, without which the IC is not complete and cannot function to process the electrical signals and information. These facts tell us that this is not a mystery; these were serious omissions by Kilby and not envisioned by Kilby at that time. But it is a mystery how all this important information was ignored and swept aside by the USPTO in granting the patents to Kilby, and by the key technical and patent personnel all over the world who simply accepted Kilby as the inventor of the IC. Moreover the authors of books on the invention of the transistor and of the IC, and also some who wrote their PhD theses in History on the science and technology of these inventions also ignored or did not understand this important information.

4.3 The quintessence of Nobel's Will is that the Nobel Prizes shall be awarded to those irrespective of nationality who, during the preceding year have conferred the greatest benefit on mankind. Nobel Prize is not awarded in the field of Engineering. The invention of ICs belongs more to the field of engineering rather than any other basic field of science such as Physics, Chemistry, etc, in which the Nobel Prizes are awarded. Nevertheless the impact of the ICs on almost all the other basic sciences has been so huge in the last few decades that their invention definitely merited a Nobel Award. The ICs are indispensable to do almost any kind of standard and advanced work in all the fields included in the original Nobel Award list.

The Nobel Prize in physics[7] was awarded jointly to Alferov, Kroemer and Kilby, and listed in this order, in 2000. Noyce had died in 1990; the Nobel Prizes are not awarded posthumously. As best as I can judge, had Noyce not died, he would have been definitely included in this award. Perhaps then the entire Nobel Prize award would have been worded and even awarded differently. The inventions of Kilby and Noyce did not involve any basic contributions to physics. However, the work of Alferov and Kroemer did involve basic contribution to physics.

The citation for the above Nobel award to the co-winners Alfred, Kroemer and Kilby was published as “for basic work on information and communication technology". The part of the citation specific to Alferov and Kroemer was written as, "for developing semiconductor heterostructures used in high-speed- and opto-electronics", and the part of the citation specific to Kilby was written as, "for his part in the invention of the integrated circuit". The Nobel Prize money was distributed as 1/4 each to Alferov and Kroemer, but 1/2 to Kilby. The citation of the Nobel Award to Kilby did not explain what was his part to invent what kind of IC? Kilby's citation in the Prize was incomplete and inconsistent with his contribution to the purported invention of monolithic-ICs for which he was given the Nobel award. No explanation has been offered so far by the Nobel Committee for the vague and imprecise citation of such an important world renowned Prize. Kilby's demonstration of hybrid IC, subsequently used in microwave ICs to this day, such as the cell phone, was not recognized by the Nobel Committee, at least not explicitly.

I had written communications in 2006 with two members of the Nobel Committee which was responsible for the Nobel award in Physics in 2000. For the sake of discretion, I have chosen to refer to them only as Dr. MNC-1 and Dr. MNC-2 (for details see Chapter 12). To the best of my knowledge, I was the first to raise the issue of the incomplete characterization in the citation of the award to Kilby. They had invoked Nobel's Will, and declined to answer my questions. An aura of mystery was created in these communications because neither clarifications of Kilby's invention nor any further recourse to get them were given. Any implication of Kilby's hybrid demonstration of the IC now still used in microwave IC such as the cell phone could have been explicitly stated by the Nobel Committee without ambiguity, if the Nobel Committee had recognized and intended to award such an application of the hybrid IC. However, Kilby was not the first to demonstrate the concept of hybrid-ICs.

The above mystery was heightened also by the refusal of Nobel Committee to offer explanation for an additional fact which struck me as unusual. This fact was that Kilby was given twice the amount of financial award, even though his contribution did not involve Physics, than to each of the other two co-recipients whose fundamental contributions did involve Physics. Such a monetary award was unlike the equal amounts given in the Nobel Prize in Physics awarded to Shockley, Bardeen and Brattain in 1956 for their invention of the transistor earlier.

The winners in a 3-person Nobel Prize award are listed alphabetically most of the time, especially if the monetary part of the award is distributed equally. However this procedure was not followed in listing Shockley, Bardeen and Brattain in 1956. Alphabetical order was not followed either in the listing of Alferov, Kroemer and Kilby in 2000, and Kilby's name was last in the sequence even though he was given twice the amount than given to each of the other two.

It is generally known that the highly revered group of the Nobel Committee acts as a powerful closed institution which feels strongly that they do not owe any explanation to anyone regarding their choices and decisions. Without casting any aspersions on any party concerned, respectfully and punctiliously I only wish to state that the manner in which Kilby's Nobel citation and award had been handled was quite inexplicable. My communications with the Nobel Committee and their refusal to shed light on both the citation of the award and the double amount of the financial award to Kilby, had created more intrigue to the mystery. Nevertheless one cannot obliterate the facts as published by the Nobel Committee itself and elsewhere in the literature. They are cast in concrete and therefore stated as such in this book. However I have done further research using the original Nobel website on the Nobel Awards in Physics throughout their entire history of existence. Based on my research, I can offer an explanation only for the sequence of listing of the names, and the unequal financial awards by the Nobel Committee to Alferov, Kroemer and Kilby. But I still cannot fathom the imprecise citation of the award and the choice of Kilby by the Nobel Committee, which remains a mystery. For details, see Appendix 7 and Chapter 12.

4.4. To repeat and elaborate further, Kilby's reduction to practice of his invention was that of a hybrid-IC, not a monolithic-IC.[12,13] He had used mesa technology to fabricate and isolate the devices in germanium (Ge), not silicon (Si), and he had used gold (Au) wires bonded to the device chips (transistors, diodes, resistors and capacitors) to connect them electrically. The gold wires flopped all over the chip from one device to another; they were not the monolithic IC interconnects in which evaporated-thin and etched-narrow aluminum films (adherent to the silicon-di-oxide films) to electrically interconnect the devices on a single silicon chip are used. This is not a mystery. It is a documented fact given in many publications (see

Chapter 7). Figure 1.1 shows the photograph of Kilby's reduction to practice of his invention. Wire bonded interconnects can be seen clearly going from one device to another flopping in air above each of the device chips.

4.5. Noyce's invention[2] gave the procedures to fabricate silicon monolithic-ICs which have been used for the past 50 years to this day (1959–2009) in large volume manufacturing. But he had used planar technology invented by Hoerni[8] and p-n junction isolation invented by Lehovec.[9] The credit due both Hoerni and Lehovec for their crucial contribution to the invention of the IC had been overlooked and ignored in the entire technical literature, until my call.[12] The credit at least due Hoerni was acknowledged recently by Riordan[51] only after my paper[12] had stated explicitly that the contributions from both Hoerni and Lehovec were indispensable, without which the monolithic-IC, as we know it today could not have been made.

Another key contribution used in Hoerni's invention at Fairchild Semiconductor R&D Laboratory was by Sah[10] in 1958. He had given the experiments-based theoretical design curves for SiO_2 layer thicknesses needed to mask against the dopant impurity for selective thermal diffusions in order to make planar junctions of desired geometries. This was a critical step in fabricating Hoerni's planar transistors, not recognized by the others. Sah's work was the enhancement of Frosch and Derrick's[11] work done earlier which had not given the design curves of the thickness of the SiO_2 needed for masking against the high-temperature diffusion of the phosphorus impurity to make the n+/p junctions. For details, see Chapter 6. As it is well known that the thermal diffusions of phosphorus and boron were supplemented later by the ion implantation technology.

Noyce did not acknowledge Hoerni[8] and Lehovec[9] in his key IC patent.[2] Why? The reasons can be debated, nevertheless this is a fact whose mystery remains unexplained. The facts also tell us that the reduction to practice of his invention was a team effort who had used Noyce's step-and-repeat lithography camera. The contributions were made by several key co-workers who had worked in the 100-person-strong Fairchild Semiconductor R&D Laboratory of which he was the Director of Research. Whether or not their indispensable contributions were ignored by Noyce's patent lawyer intentionally, cannot be ascertained, but it was more likely that Noyce did not know who actually made the contributions and could not single out one person except those other single-inventor patents also filed during that period at Fairchild. However, it can be surmised that Noyce's single-author IC patent may not have been the likely cause of the departure of several of his eight Fairchild co-founders as perceived by all subsequent semiconductor history authors. These departures may have been due to more lucrative opportunities elsewhere. As an example, Eugene Kleiner went on to found Kleiner-Perkins, the famous venture capital firm. They were all hired previously by Shockley as the core of the Shockley startup. This is a fact, not just a good story, which is likely to be pushed aside or fogotten by the subsequent sucesses of those who left for the greener pastures and personal professional interests of 1960's.

Additional patent-based key points of Kilby's and Noyce's inventions shall be given later in subsequent Chapters 7 and 8 in this book. However the few points listed above should serve as a good start to trigger and focus the readers' curiosities to know about the mysteries and facts of the invention of ICs, the invention which is used in all electronic gadgets that impact every aspect of our life and existence, now and forever.

5. My qualifications

The readers may be curious to know about who am I and what my qualifications are that could be adequate to point out the inconsistencies in the history of one of the most important inventions of mankind? I have already discussed these qualifications in the Preface, where the reasons for including my IC concepts briefly were also given. I have followed the advice given to me by Gordon Moore.[55] In lieu of repeating in detail here, I ask you kindly to read Appendices 1 and 2 at the end of this book, my publications[12,13] on the invention of ICs, and also the commentary given by Jeff Marque[14] on my publication.[12] They are copied in Appendices 3 and 4, and in Chapter 11.

6. Getting history right

Getting history right is an important matter. It is in that spirit that I am writing this book about the invention of integrated circuits (ICs). The invention of ICs has been one of the most important inventions of the 20th century which has revolutionized mankind forever. They are used worldwide in many if not all fields and applications (partial list is given alphabetically): banking, biotechnology, communications, computers, education, entertainment, government, hospitals, internet, medicine, nanotechnology, research, travel, and others, and in every commercial, defense and industrial businesses. All the electronic systems in these applications use much more advanced ICs such as Ultra Large Scale ICs (ULSICs) than the ICs invented originally. However, the stems of all ULSICs are rooted in the basic invention of the ICs. The ULSIC business has now grown to multi-hundred billion dollars annually which is also the heart and soul of all electronic systems market of trillions of dollars per year. It appears that the future growth of ULSICs and its impact on newer businesses shall still be forever increasing. Therefore it is important to know what were these basic inventions of the ICs, who invented them and how.

Getting history right is also a difficult task, especially if the subject matter is of a fundamental importance and its prevailing erroneous view has lasted for a long time, viz., a few decades. This is particularly difficult for the person setting the records straight if he/she, though qualified and having first hand knowledge, is not "famous" and also belongs to a minority group different than those of the majority whose history needs to be corrected. This problem gets exacerbated further when the persons of the majority have been regarded popularly as icons for decades.

7. The case of Einstein

The case of Einstein will be cited here, not to set history right because there was nothing wrong with his work, but as an example of defending under difficult circumstances what was right for physics and humanity. Max von Laue had defended Einstein's work which was being criticized as being Jewish in character by the others during the period Hitler's power was ascending in Germany. Even though Laue belonged to the majority group and Einstein to the minority, it was not easy for Laue to stand up to the other well known physicists in the majority group who were trying to discredit and criticize Einstein unfairly. It took a few years for Laue to set the records straight about Einstein's discoveries, but he succeeded eventually. Just imagine the compounding of the problem had the situation been reversed. Had Laue made the errors in his work and Einstein had corrected and tried to document them, this would have made Einstein a pariah being a member of the minority group. Even though Einstein's main motive to do this would have been only to set history right, he would not have been given any kudos for this.

8. Why getting history right is important?

Being cognizant of the yore, while forging ahead with the future by innovations is a prudent wisdom to follow, so that the past mistakes shall not be repeated. The adage "Those who do not learn from their past mistakes, are condemned to relive them" has been proven to be right over and again throughout the entire history of mankind including scientific research. The inspiration for the younger generation to innovate for the future is provided by the leaders of the past. If the past accomplishments are misrepresented by the spin meisters of the present, it negates this key process of progeny of innovation for the future. Therefore getting history right is very important.

Society is comprised of a spectrum of human beings of different ages, backgrounds, education, careers, ethnicity etc all over the world. For it to function, survive and progress in a civilized manner, many prudent actions must be taken. To discuss all aspects of what they are is a daunting task well beyond the scope of this book. However, an undisputable and important task is that of getting history right for the society. While it is almost impossible to do this unequivocally in several fields affecting the society (e.g., politics), it is relatively an easier task in the fields of exact sciences and engineering. We shall narrow down from the morass of even these precision fields to focus only on the invention of ICs in this book.

The invention of ICs has been one of the most important inventions of the 20th century which has revolutionized mankind forever. In some respects, the impact of this invention on mankind far exceeds that of Einstein's discoveries made earlier. Nevertheless, the fundamental aspects of IC are rooted in Einstein's contributions among other pioneering discoveries. To re-emphasize, ICs are used worldwide in many applications in various fields, and almost nothing is possible today without using the ICs and their associated technologies. As best as one can extrapolate into the future, their applications even in the uncharted territories yet to be dreamed of, shall forever increase. Therefore it is important to know what is true and what is not about the invention of ICs. Erroneous claims have been made and wrong conclusions have been drawn in the past regarding them in the literature. Both documented and undocumented facts have been used for such claims. While the latter may provide an intriguing and thought provoking type of a mystery novel, they do not quantify and prove beyond any reasonable doubt the truth of an invention.

9. Documented facts

The documented facts are the only way to get history right especially in science and engineering. I concede, however, that even the documented facts in these fields of exact sciences and engineering may have resulted from intrigues and usurping other people's rights and contributions. Such discussions are also debatable and beyond the scope of this book, although brief comments will be made only on a few relevant issues directly concerning the invention of ICs. Therefore the main focus of this book is to give and discuss the documented facts of IC invention. Even the documentations have left several key questions still unanswered after so many years regarding this important invention. They will be discussed briefly at the end in Chapter 15. Comments shall also be made on the support technologies key to the invention and progression of ICs, which have not been given their due recognition in the literature so far.

To get history right is the responsibility of subject-qualified people, and such an important task should not be left solely to the so-called science history writers, many of whom have had little or no first hand knowledge and experience or college training in the field. I have been involved in science and technology from the early years before the ICs were invented, during their invention and their advancement to the current super chips, and their future directions. The IC inventions were discussed in the earlier papers[12,13] in a comprehensive technical manner meant for the specialists in the IC field.

Einstein's answer to the question, "What should the younger generation be taught?" was a simple word, "History." Another cliché ascribed to Einstein is, "Imagination is more important than knowledge. While the latter has limits, the former is limitless!" Even though these sentiments have been expressed by many over millennia, Einstein is credited with them as he has been better known in the modern era. A key implication derived from these comments of Einstein is to get history right. So this statement has been made here to reinforce the importance of getting history right, especially regarding the IC inventions by objective and thorough analyses of the documented facts.

10. What are documented facts?

Similar to living in a "Fool's paradise", one is apt to misjudge what is right and what is wrong if it is not clearly understood what the documented facts are? Therefore at the outset, we shall describe what are they?

Documented facts which are used in the scientific and technical world to assign an invention are the patents issued by a bona fide legal agency of a government such as the United States Patent and Trademark Office (USPTO) in the USA or similar agencies in other countries of the world, and the research publications, pre-publication and now also post-publication or post-public-disclosure, in peer reviewed professional journals. The latter have less clout than the former in legal contests. However for professional recognition as well as awards of prizes like Nobel Prize, research publications wield an equivalent clout if not higher than the issued patents. While this practice holds true most of the time, however, it was not the case in the recognition given to Kilby "for his part in the invention of the integrated circuit" cited by the Nobel award committee[7] in 2000 (for details, see Chapter 12).

Issued patents have sub-categories of requirements of the documents such as record of original concept (e.g., witnessed notebooks, patent disclosures), filing date, and reduction to practice of the invention. The last criterion is quite debatable as it has not been deemed to be absolutely essential in many cases to claim the invention and receive a patent.

Writing of the patents itself is a highly specialized legal field in which its specifications (figures and the text) and the claims should be understood by any person conversant in the state of the art, and be able to reduce the invention to practice. All the claims of the patent must be supported clearly by its specifications.

Documented facts as described above have been published and analyzed in the recent paper[12] for the first time in the literature in a comprehensive manner to clearly characterize the inventions of ICs by Kilby[1] and Noyce.[2]

11. All ICs sold from day one have been Si monolithic-ICs

All the ICs manufactured and sold from the very beginning when they had only a few transistors on a silicon chip to those currently having several billion transistors per chip, have been the monolithic-ICs using silicon (Si). (As stated earlier, the bybrid microwave ICs, widely sold, such as in cell phone, are excluded from these deliberations.) As recently as in 2006, several research historians[16,41] have erroneously heralded Kilby's invention in 1958 as the advent of the monolithic era. Noyce's invention as documented in his patent was simply to prescribe how a monolithic-IC was to be made using Si, but he did not reduce his concepts to practice. It was done by the others who were members of Noyce's Research and Development Laboratory of which Noyce was the director at that time. Gordon Moore became its director later. The planar technology mandatory for fabrication and the electrical isolation of devices necessary in the ICs were respectively invented by Hoerni,[8] a member of Noyce's Laboratory, and Lehovec[9] who was with Sprague Electric Company. However, even the invention of the planar technology ascribed to Hoerni can also be questioned. It was derived by Hoerni from a combination of associated technologies on which the key technical work was done earlier by several others (see Chapter 6 for details). What is the monolithic concept and how do the monolithic-ICs differ from the hybrid-ICs, has also not been understood or delineated properly in the literature so far. This will be explained in Chapter 4. Details of the facts of Kilby's and Noyce's inventions shall be given with proper documentations in Chapters 7 and 8 respectively.

Neither Kilby nor Noyce contributed directly to the advanced technologies or concepts used currently to manufacture the Ultra Large Scale ICs (ULSICs) and those required for the future ICs, e.g., 3-dimensional-ICs (3D-ICs), Ultra Performance ICs (UPICs), and IC-based systems such as systems-on-a-chip (SOCs). Noyce, however, did make a very significant additional contribution to the entire field of microelectronics by co-founding Intel Corporation with Gordon Moore which has been the leading manufacturer of ULSICs in the world. A great majority of all the advanced technologies are developed and implemented in large volume manufacturing at Intel. Impact of the past and current inventions of ICs on Moore's Law which has guided the entire microelectronics industry, and future directions, shall also be presented in Chapter 13.

12. Three questions need to be answered up front

In addition to giving the background information about the invention of the ICs in this chapter on Introduction, three questions also need to be answered up front:

12.1 Why do we need to know the important facts and to get the clarifications now after the invention of ICs about 50 years ago (or 55 years depending on when you start counting)?

12.2 Why nobody else has clarified some of the key technical facts of their inventions by Kilby and Noyce so far? Did Kilby and Noyce borrow their ideas from the others?

12.3 What are the questions on the invention of ICs which are still unresolved, and why have they not been addressed so far?

The answers to the above three questions are given in Section 18 below after discussing the relevant information in the following sections.

13. Victory/success and defeat/failure

As it is well known, "Victory/success has many fathers, but defeat/failure is an orphan!" This fact has been expressed in many different parts of the world from ancient times to the present in respective languages and cultures in their own unique and inquisitive ways. The invention of the ICs has been perhaps the most successful event in the entire history of technology developments in the world which have contributed to so many fields of science and businesses, and revolutionized mankind. The acronym IC for integrated circuit has been used in the literature generically for any kind of integrated circuit, without explaining what specifically it is for. This has caused some confusion, because when it is used for a hybrid-IC also, the demarcation between it and a monolithic-IC is debatable and not unequivocally separated. However, as it will be explained in Chapter 4 of this book, the use of acronym IC is predominantly for, and from accuracy point of view should be restricted to, the monolithic-ICs only. From the very beginning to the present, all the integrated circuit products sold in the semiconductor industry have been monolithic-ICs.

Despite the above well known adage regarding victory and defeat, it is interesting to note that not many "fathers" have come forward to claim the parentage of the invention of the ICs during the past 50 years. The two "fathers", viz., Jack Kilby[1] and Bob Noyce,[2] have been regarded as the undisputed inventors of the ICs, except that a few key facts even about their inventions have not been scrutinized carefully so far in the literature. Several others also did make key contributions to make the monolithic-ICs a reality, which are the true ICs, not the hybrid-ICs, being manufactured all along in the past 50 years. These monolithic-ICs are the heart and soul of the multi-hundred-billion dollar per year IC industry, which is also the core of the multi-trillion dollar per year electronic systems industry. However, while a few have been recognized (cf. Rostky[15]) for their contributions to make monolithic-ICs a reality, others have been literally "walked over". Was it due to the hero worship of Kilby and Noyce, and/or due to the lightening speed at which the technology and business developments with huge profits that took place, and that the timing was propitious for them to happen? These are debatable issues. The purpose of this book is not to address this complex subject which is hard to quantify, but to present several technical facts primarily about Kilby's and Noyce's inventions of ICs and key contributions of a few others which have not been clarified and documented before. Therefore, it is important to know the truth about who invented what and how, even after 50 years since the patenting process of these inventions was begun.

A few authors such as Kilby[1,19] (who is widely regarded as, and was, the co-inventor with Noyce[2] of the ICs), Wolff,[3] Rostky,[15] Riordan & Hoddeson,[16] Berlin,[17] Reid,[39] Lee,[40] Brock,[41] and Lojek[42] have tried to tell the story of the invention of ICs in their respective ways. While Kilby[21] himself has given a historical account of the invention of the ICs in 1976, however he addressed and discussed the technical aspects of his invention and the patent[22] only recently[19] in 1998, and made some comments also on Noyce's invention and his basic IC patent.[2] Noyce[43] described the IC as conceived at Fairchild, and referred to the work of Kilby (ibid), Hoerni,[8] Lehovec[9] and others, but did not describe the technical details of their patents in his paper. The authors in references 15–17, 39, 41, 42 do not address the technical issues of Kilby's and Noyce's IC inventions and their patents, and they have ascribed Kilby's invention incorrectly to be that of a monolithic-IC. Perhaps this may be due to their efforts more as science history writers, rather than as scientists and engineers who are educated and trained to have the technical precision and knowledge and contributed first hand to solid state devices and IC technologies. Even Kilby's later comments[19,44] are incomplete engineering physics at best.

Wolff[3] gives an early account of the genesis of IC including predictions of Dummer[4] in England, efforts of Kilby[23] at Texas Instruments (TI), Noyce[2] at Fairchild, and Lehovec[9] at Sprague. However, Wolff[3] does not refer to the work of Johnson[5] of RCA and Stewart[6] of TI. While his descriptions of the work of Noyce and Lehovec are quite correct, but that of Kilby's requires some clarification. The caption of Fig. 1 in Wolff's paper reads, "A page from Jack Kilby's notebook of July 24, 1958, where he first recorded how resistors, capacitors, and transistors could be made on a single slice of silicon." This part of making the devices is aptly credited to Kilby, but it is only a small as well as incomplete part of fabricating devices for the chip; it does not even specify the need for interconnecting and isolating the devices. Also, these devices must be made with planar, not mesa technologies. Nowhere in his patents or papers Kilby mentions or uses planar technology; instead he uses mesa technology. Therefore, while Kilby's enunciation of the concept to fabricate various devices on a single chip is to be recognized, his actual accomplishments were not for the correct monolithic fabrication of even just the devices used in the last 50 years since the beginning of manufacturing of the ICs. Also, the key role of interconnects to electrically connect these devices is not explained by Wolff[3] who simply quotes from Kilby's notebook as their fabrication with "conductive material evaporated to connect the transistor emitter and base to the circuit, or small wires might be attached by thermal bonding." Kilby prescribes in his patents evaporation of metals through metal masks, and wire bonded interconnects which are not used in monolithic ICs. Until the monolithic interconnects are also fabricated, which must be adherent to the insulator layers without shorting to the regions adjacent to the devices and each other, monolithic IC is not complete and will not function.

As a journalist, Reid[39] has done a good job of writing the story of "The Chip", however, it is meant for laypersons. While he does not give the technical details of the invention of ICs, he presents the various key issues quite well. Lee[40] discusses mostly "The (Pre-) History of the ICs", and gives only a capsule of Kilby and Noyce's inventions at the end of his paper without analyzing their technical details. The recent book by Lojek[42] gives an interesting and compelling account of the "History of Semiconductor Engineering", covering several of the areas of semiconductor engineering as it developed from the early years. While it is almost impossible to give the technical details of every issue in its entire field, he has tried to give the essence of a few of them. He has provided an incredible amount of documentation, some of which is rather provocative and debatable. Regarding the invention of ICs, Lojek's[42] statements at the outset (p. X. lines 15–17) are quite correct: "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." To emphasize, only these statements by Lojek are undisputable in my opinion. His description of the others in "the group of inventors" is debatable, incomplete, and controversial due to lack of proper documentation.

Even though the internet and information technologies have enabled communications of all sorts better than ever in the history of mankind, the facts regarding one of the most important inventions, viz., the ICs, are still not known clearly to a majority of the people. This is true also even for many of the thousands of scientists and engineers working in the microelectronics field today.

Similar to the statement above regarding victory/success and defeat/failure, it will behoove us to recognize also that many an invention is not without some controversy about who the original inventor(s) was (were). My intent is not to create any controversy, or in any way to diminish the pioneering contributions of Kilby and Noyce, but the key purpose of writing this book is to clarify and present the facts. Like celebrities, only those inventions are newsworthy and deserving of critical and thorough investigation, which make a major impact on the business and/or human life. "The Invention of ICs" is such an invention (see Saxena[20]). Therefore, its story merits a more thorough technical scrutiny than it has been done so far in the literature.

14. Disclosure of the basic concept for ICs by others earlier than Kilby

Kilby's suggestion to fabricate multiple devices within a single piece of semiconductor was of course a key contribution, but it was only a small as well as incomplete part of the total invention needed to fabricate the ICs. Independent of Kilby, similar suggestions had been made by other authors, e.g., Geoffrey Dummer[4] in England, and by Harwick Johnson[5] of RCA and Richard Stewart[6] also of Texas Instruments (as Kilby was from there too but joined TI later) right here in the USA, earlier than Kilby.

If we restrict to the concept of fabricating multiple devices in a single piece of semiconductor as the key invention of IC by Kilby, for which he was also awarded the Nobel Prize, then we must recognize the documented contributions of the others made earlier than Kilby. Why were they ignored? Did Kilby derive his key ideas from them but did not acknowledge them? Why could someone do that and be allowed by the peers and the professional societies to get away with it?

For the sake of whetting the appetite of the reader at this point, I shall quote the key ideas of the IC invention described in their respective patents and paper by Kilby, Dummer, Johnson and Stewart briefly as follows:

14.1 Quotation of the basic concept of IC invention stated in Kilby's patent[1] no. 3,138,744, "Miniaturized Self-contained Circuit Modules and Method of Fabrication"; filed May 6, 1959; issued Jun. 23, 1964*; Column 1; Lines 55–62:

"... *To that end, I have proposed in my pending application for patent, Serial No. 791,602, filed February 6, 1959, that* *various circuit elements including diodes, transistors, and resistors all be formed within a single block of semiconductor material, thereby eliminating the necessity for separate fabrication of the semiconductor devices and the interconnections as mentioned above. ...*"

Kilby did not state the above concept in any of his other patents.

14.2 Quotation of the basic concept statement from Dummer's paper,[4] "Electronic Components in Great Britain," Proc. Components Symp., Washington, DC, p. 15–20, May 6, 1952 (No patent filed by Dummer); second paragraph on p. 19:

"*At this stage, I would like to take a peep into the future. With the advent of the transistor and the work in semiconductors generally, it seems now 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 directly by cutting out areas of the various layers.*"

14.3 Quotation from Harwick Johnson's patent[5] no. 2,816,228, "Semiconductor Phase Shift Oscillator and Device"; Filed May 21, 1953; Serial no. 356,407; issued Dec. 10, 1957; Column-4; lines 62–67, Claim 4.

"*A semiconductor phase shift network comprising a* ***unitary semiconductor body*** *including a plurality of series-connected alternating elements of semiconductor material of one type of conductivity and P-N junction elements, and bias voltage means connected to said P-N junction elements for varying capacitance thereof.*"

14.4 Quotation from Richard Stewart's patent[6] no. 3,138,747 — "Integrated Semiconductor Circuit Device"; filed Feb. 12, 1959; issued June 23, 1964*; Column 1; lines 29–42:

"*The invention improves over the prior art circuits in that* ***the necessary circuit elements such as the load resistor may be made an integral part of the semiconductor element****. One such semiconductor element according to the present invention replaces several transistors required in the circuits of the prior art performing the same function.* **The interconnecting circuit wiring is thereby eliminated or reduced.** *Also the gates of the "nor" circuit of the present invention provide amplification in addition to performing a logical function and the gates are well matched since they are basically one transistor.*

The fact that the entire circuit is embodied in a single transistor element allows miniaturization of the circuit heretofore not realizable."

15. Brief comments on the basic concepts of IC invention documented by Kilby, Dummer, Johnson and Stewart given above

For the sake of continuity and the readers to get a sense of intrigue in the invention of ICs, brief comments on their respective versions of concepts quoted above, are given as follows. Detailed comments on the basic concepts of the IC invention as documented by Kilby, Dummer, Johnson and Stewart above in Section 14 are given in Chapter 9.

15.1 Kilby had filed his patent(s) in 1959; some were issued in 1964, and others later. However, Kilby's key patent no. 3,138,744, the only patent in which he had stated his basic concept of IC invention, was filed on May 6, 1959, and was issued on Jun. 23, 1964*. Kilby had claimed priority of earlier filing on Feb. 6, 1959, of his original application (OA) but this was denied by the USPTO. Its filing date was recorded as May 6, 1959, or that no filing date was recorded at all. Nevertheless based on OA, patent no. 3,138,743 was also issued on the same date as 3,138,744, viz., on Jun. 23, 1964*. Strangely enough, Kilby kept on referring to his patent no. 3,138,743 in his later patents and papers, although he had not stated his basic IC concept in this patent. Both of these patents were assigned to Texas Instruments (TI). **The asterisk on the issue dates for these two patents of Kilby (3,138,743* and 3,138,744*), as well as Stewart's patent no.**

3,138,747* given below (see 15.4), is to draw the reader's attention that they were all issued by the USPTO on the same date, and all were assigned to Texas Instruments (TI). This practice is not commonly done by USPTO. It is somewhat unusual that all three patents were issued on the same date, especially when the filing date of Kilby's patent no. 3,138,743 was deemed controversial, the two Kilby's patents were numbered consecutively, Stewart's patent was numbered by 3 more in the sequence, and all were issued much after Noyce's patent even though filed earlier than him. For details of filing and issue dates, and further comments, see Chapters 5, 7 and 9.

15.2 Dummer did not file for a patent. But he had first published his concept on May 6, 1952, almost as an afterthought for an IC, without defining what kind of IC could be fabricated: hybrid or monolithic? Kilby's description in his patent no. 3,138,744 filed on May 6, 1959 was similar and limited to the same criteria as Dummer's in 1952. Kilby had attended Dummer's presentation in 1952, so it is likely that Kilby may have derived his ideas from Dummer. He seems to allude to it in his Nobel Lecture in 2000. However, this cannot be proven beyond any reasonable doubt. Nevertheless, despite their incompleteness and similarities, clearly Dummer's documentation of the basic concept pre-dates Kilby's.

15.3 Harwick Johnson gave essentially similar concept in his patent no. 2,816,228 to fabricate a "unitary body". Johnson's patent describes the concept of forming a transistor and another portion formed as a controllable phase shift network or delay line (for example, resistance-capacitance), the two portions being related and interconnected to provide the desired function in a unitary semiconductor body. This is similar to, if not more than, the monolithic concept described by Kilby. It describes the concept of fabricating transistor, resistor and capacitor in a unitary semiconductor body, but it also specifies interconnecting them for a desired function which was not given by Kilby. Johnson had filed his patent on May 21, 1953, and it was issued on Dec. 10, 1957. So clearly, Johnson patent also predates both in filing and issuing of Kilby's patents.

15.4 Richard Stewart's patent no. 3,138,747 was filed on Feb. 12, 1959, and it was issued on June 23, 1964*. The asterisk on the issue date of this patent and the two patents of Kilby (3,138,743* and 3,138,744*) given above, is to draw the reader's attention that they were all issued by the USPTO on the same date, and assigned to Texas Instruments (TI). Stewart had been working at TI before Kilby had joined it in 1958. Why was Stewart ignored when he had given essentially similar concepts to Kilby's, and all the kudos were being given to Kilby, is a mystery. Stewart's disclosure of the basic concept in his patent filed ahead of Kilby's patent no. 3,138,744 in which Kilby's concept was stated, was quite similar. Stewart wrote, "*... the necessary circuit elements such as the load resistor may be made an integral part of the semiconductor element. One such semiconductor element according to the present invention replaces several transistors required in the circuits of the prior art performing the same function. The interconnecting circuit wiring is thereby eliminated or reduced.*" Filing of Stewart's patent no. 3,138,747 predates the filing of Kilby's patent no. 3,138,744. For detailed discussion, see Chapter 9.

16. Concepts given by Saxena in 1954

As already written in Section 8 of the Preface, even though I had published a paper in 1953 based on which I had also given the concepts for ICs independent of and earlier than Kilby and Noyce, I shall not discuss them in detail in the main text of this book. However, for the sake of completeness of historical record, I shall defer it to Appendix 2.

17. Inputs for Noyce's patent and investigation of Kilby's patents

My technical inputs which had helped Noyce's IC patent to be awarded in 1961 ahead of Kilby are documented in two papers.[20,28] Basically, the key issue was of the interconnect metal to be adherent to the insulating film, SiO_2. My inputs were that aluminum (Al) specified by Noyce was correct, whereas gold (Au) or copper (Cu) by themselves for interconnects specified by Kilby were incorrect. For further discussions, see Chapter 8.

While investigating the details of Kilby's patents, I have received some new information about them (see Chapter 5) as recently as on September 26, 2005, and on November 02, 2005, from the US Patent Office (USPTO). They had not been reported in the literature previously until my papers[12,13] were published. These papers also contain brief accounts of the key technical facts of Kilby's and Noyce's inventions which had not been published in the past.

18. Other aspects which contributed to the invention and fantastic success of ICs

There are many other aspects of ICs, e.g., manufacturing equipment, materials, processes, design, packaging, applications in systems, etc, whose inventions and developments also need to be scrutinized carefully. They were, and still are, crucial to the fantastic success of the IC industry. However, this huge subject also shall not be discussed in this book. The main purpose of this book is to focus on only one aspect of the ICs: The Invention of ICs.

19. Answers to the three questions raised in Section 11

The information given above in sections 12 to 16 provides the answer to the first question raised in Section 11: "Why do we need to know the important facts and clarifications now after the invention of ICs 50 years ago (or 55 years depending on when you start counting)?" See also the next Chapter 2. All throughout this period of time, the important facts and clarifications of the invention of ICs have not been documented correctly. My attempt to write this book is to do just that.

The second question, "Why nobody else has clarified some of the key technical facts of the inventions of ICs by Kilby and Noyce so far?" is not easy to answer. Nevertheless I have given in Chapters 7 and 8, these key technical facts and why they are important. Hundreds and thousands of qualified personnel (scientists, engineers and patent attorneys) all over the world must have noticed these technical facts. Why they did not address and document them so far is surprising indeed.

The answers to the last question, "What are the unresolved questions still on the invention of ICs, and why have they not been addressed so far?" are also somewhat difficult. However, these questions and comments are given in Chapter 15.

20. For whom is the book primarily intended and at what level?

This book is primarily intended for all scientists, engineers and managers in the IC industry, as well as undergraduate, graduate students, professors in electrical engineering, physics, materials engineering and chemistry in universities, and not the least, the patent attorneys. The level addressed will be for a broad category of practicing engineers in industry, undergraduate and graduate students in academia, attorneys in law, and venture capitalists. However even the laypersons who may be interested in finding the truth about the invention of ICs, should be able to follow all the documented facts without getting mired in their technical details and jargons. They may skip reading the various original patents and the technical papers, which may be of interest only to the specialists in microelectronics.

Many of the engineers and scientists, even those who are currently in the fields of microelectronics, computer and information and communication technologies (ICTs), have taken Ultra Large Scale Integrated Circuits (ULSICs) for granted. While some may know how these ULSICs came to be, and how they emerged from the original ICs to the super chips of today, many are probably too busily immersed in the narrow topic and task of developing their respective advanced technologies to meet the target dates demanded by their jobs. As it is well known, these billion-device super chips are used in many applications in various fields of education, research, medicine, government, and in the entire commercial, industrial and defense industries. Therefore, even though the number of engineers, scientists and other workers in these fields may be huge, those who really understand the overall facts regarding the invention of the original ICs may be rather small. In order to appreciate the mind boggling progress of the entire IC industry, it will be helpful to understand how did it all begin, and to know the facts about how the original ICs were invented and by whom? Knowing the true history of the invention of ICs and their development can only help in having a better insight into the future technologies needed for the even more advanced chips.

This book may also be used as the key text book to establish graduate level courses on “The Invention of ICs which Revolutionized

Mankind Forever" in universities. These courses may be established in various departments such as Physics, Chemistry, Electrical and Computer Engineering, ULSI Design, Materials Engineering, Mechanical Engineering (Design of Processing Equipment), Entrepreneurship and Innovation, Business School (Marketing and Management in High-Tech Industries), and Social Sciences (Impact of High-Tech Innovation on Quality of Human Life). The core material may be extracted from this book and augmented with additional advanced support material to establish such graduate level courses.