Peter H. Rose - Father of Ion Implantation: The Early Years

Andrew Wittkower and Geoffrey Ryding

Abstract— **In 1996, President Clinton presented Peter Rose with the National Medal of Technology and Innovation. This paper describes his innovations in ion implantation technology which led to the award presented twenty years later.**

I - INTRODUCTION

This paper is a tribute to Peter H Rose, known widely as the "Father of Ion Implantation" [1]. Peter was born in Lincoln, England in 1925. He received a PhD in Physics from King's College, London, but he was at heart an engineer. He was also a life-long innovator and for this he was awarded the Congressional Medal of Technology and Innovation by President Clinton in 1996. Perhaps his greatest achievements were due to his ability to finish projects. For that, he realized that he could not build alone and he used his considerable charm and talents to be the leader of strong and loyal teams, and it is to this quality that we particularly pay tribute.

II – HVEC YEARS

In magic shows, a rabbit comes out of a hat; there is no "before" and no "after". In all other things, particularly in technology, there is a background to an advance (Fig 1). In Peter's case that background was his work at High Voltage Engineering Corporation (HVEC) which he joined in 1956 after completing a Fulbright Scholarship at MIT. HVEC was the worldwide producer of particle accelerators used for nuclear physics research. The largest had a terminal voltage of 15 MV and weighed more than 200 tons. Each consisted of an ion source, usually for hydrogen or helium, an acceleration section, an analysis magnet and a target chamber. These machines were HVEC's core products, but the company was also asked to build an isotope separator. Although very different in scale, except for a scanner, each contains the essential components of an ion implanter. Peter's work as Director of the HVEC Van de Graaff Research Laboratory concentrated almost entirely on ion source design although he was well aware of the other machine components.

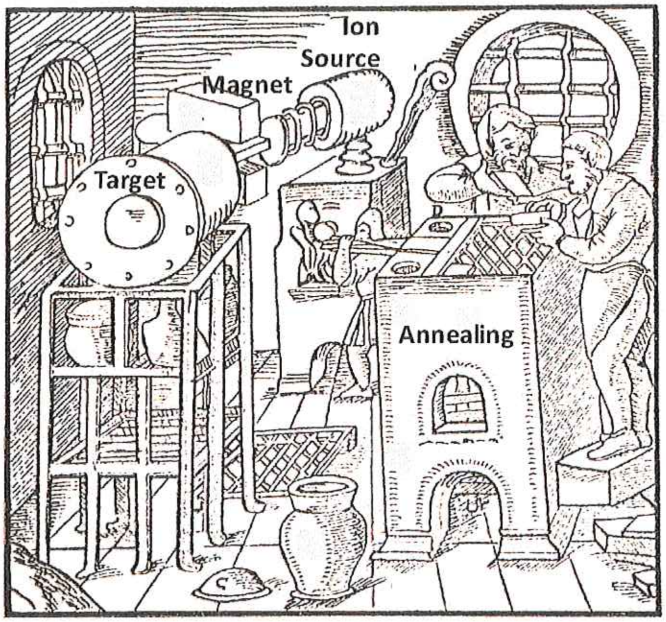

Figure 1. An adaptation of a 1556 woodcut image from "De Re Metallica" by G. Agricola. The addition of an ion implanter to the original drawing of the annealing furnace is due to M.W. Thompson [2]

In early 1969, as money for multi-million dollar research accelerators was drying up, the Laboratory was fortunate to get a contract to build a small research ion accelerator for Fairchild Semiconductor, the then premier company located in what came to be called Silicon Valley (Fig 2).

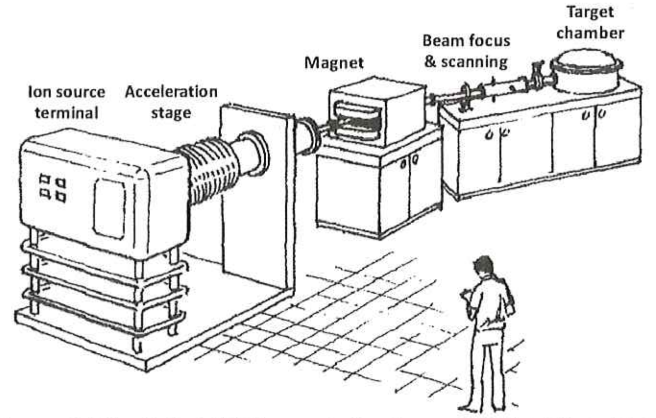

Figure 2. The Fairchild Research Implanter, Model LS-5. Note that the analyzing magnet is after the acceleration stage [3].

Andrew Wittkower (email: abwittkower@gmail.com) and Geoffrey Ryding (email: geoff.ryding@gmail.com)

It is hard to believe now, but the Fairchild R&D machine was built in six weeks, mainly using parts lifted from the HVEC stockroom. It was 30-feet (10m) long and delivered 20-microamperes of argon ions at 100 keV [3]. The target area was a hollow cube holding four 1-inch wafers which could be heated, or cooled with liquid nitrogen. Since none of us had ever seen a silicon wafer, we used thin aluminum disks as sample targets. This project gave Peter the idea that the emerging semiconductor industry might buy more robust ion implanters for production purposes, and that HVEC could have a new low-cost product. To his dismay, the president of HVEC, Dennis Robinson, was not interested.

III - THE BEGINNINGS OF EXTRION

Believing strongly in his idea, Peter told Dennis that he would develop a plan and try to start his own business, which eventually became his first start-up, Extrion Corporation (originally named Lorenz Corporation (Fig 3)). Then Dennis made a most generous and amazing offer: he would allow Peter and his team to stay on as employees until they were funded, as long as they did their planning activities after hours.

It took three months to write the business plan for designing and building an ion implantation machine for production purposes; if we could make it work, it would be the first ion implanter designed from the start for IC production.

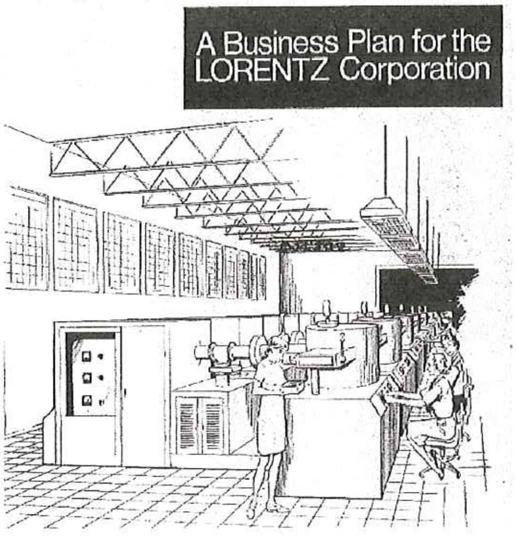

Figure 3. Cover page for the business plan for Lorentz Corp., which was later renamed as Extrion.

During this time, he gathered his team together (Peter Rose, Roger Bastide, Eli Young, Bill Starks and Andrew Wittkower, all from High Voltage and Geoffrey Ryding who was to join shortly afterwards). Since Peter realized that none of us had any business experience, he invited Pat Liles, the most popular Professor of Entrepreneurial Business at the Harvard Business School to be part of the team. It turned out that Pat was a great lecturer but had no more practical experience than we did. Later, when we had grown to a group of 10, we asked him "In a typical company of this size, how many secretaries should we have"? His reply was "How many do you think you need?" which may have worked at Harvard, but was no use to us at all.

The reason for the initial interest in ion implantation for doping purposes was its ability to greatly increase the yield of MOS transistors used in digital hand-held calculators, which at that time operated using a 9-volt battery. Prior to the introduction of ion implantation, doping was achieved by diffusion, where the peak of the dopant distribution was at the wafer surface and the junction depth, peak concentration and total dopant population (dose) could not be independently controlled. Consequently, the turn-on voltage of the resultant transistors varied and they had to be sorted into bins, only one of which held usable devices.

When ion implantation was introduced for control of the threshold voltage, with direct and precise control on the dopant dose in the channel region, the yield of functioning MOS devices was drastically increased. The technical community had begun to realize that this technique was becoming important and there were a number of competitors already selling rudimentary ion implantation systems (Accelerators Incorporated-USA, KEV-USA, Thomson CSF-France, Danfysic-Denmark, Ortec-USA, Lintott/Harwell-UK, Edwards-UK, Kasper Instruments -USA; Ulvac-Japan; also, for internal use, Hughes Research, Bell Laboratories and IBM and others [4]).

Since Peter did not know how to find a funding source, he gave our business plan to a HVEC friend (Norman Brooks, soon to be the founder of Brooks Automation) to read and asked him to suggest a route to funding. On Norman's way home, he stopped at a local hardware store, casually leaving our business plan on the counter. The next customer in line picked it up and, to our surprise, he introduced us to our eventual funding source, Gloucester Engineering. This was a company that made plastic extrusion equipment and they wanted to raise their profile by becoming more "high tech". Even though they had no experience in our field, they decided to fund us up to a level of $150,000 (roughly $1million today), a decision that they grew to regret when it became clear that they needed technical knowledge to make financial decisions. For instance, when we wanted extra cash of $1,500 ($10,000 today) for a precision high-voltage voltmeter, they baulked initially but had to give in when Peter said we could not continue without one. After we were funded, Peter went to Dennis Robinson and resigned from HVEC. When Andrew Wittkower arrived for work later that morning, Peter told Andrew that he had resigned him as well!

Extrion was set up in Peabody, MA, in a space which until then had been a leather factory. A small stream ran in a channel a foot below the floor and the smell was awful. Just next door, there still was an active leather factory with hundreds of cow skins processed daily together with an occasional dead rat. It was as far from a modern IC manufacturing facility, one with filtered air and operators in white bunny suits, as one could imagine.

IV – TECHNOLOGY ISSUES

Peter was the first to have the vision that a production ion implantation machine was needed, easy to use with a high through-put and automated wafer handling. The implant machines also had to be compact enough fit inside the limited floor space of the "clean rooms" that were beginning to be used for IC fabrication. Peter's first big technical decision in the design of our new machine was to place the ion filter magnet before the major high voltage acceleration (pre-analysis) rather than the usual post-analysis alignment (see Fig. 3). This was a radical departure from all previous designs and most people in the field concluded it would not work. It certainly was a great design risk! However, if successful, it would allow an ion implanter to be built with a significantly smaller footprint. Although Peter later thought up many other innovations and inventions, this was the one that launched today's world-wide billion-dollar implant tool industry.

The Fairchild R&D machine successfully produced hydrogen and the rare gas ions using a duo-plasmatron filament source. But the filament burnt out within a few minutes when used in a corrosive atmosphere such as BF_3, so we were still struggling with our first ion source for boron when our first potential customer turned up: Bob McPherson from National Semiconductor. At dinner one evening Andrew Wittkower casually asked him what boron source he'd been using on his research accelerator. Bob described a standard cold cathode source which he sketched on a cocktail napkin; carefully, Andrew put the napkin in his pocket. (Fig 4).

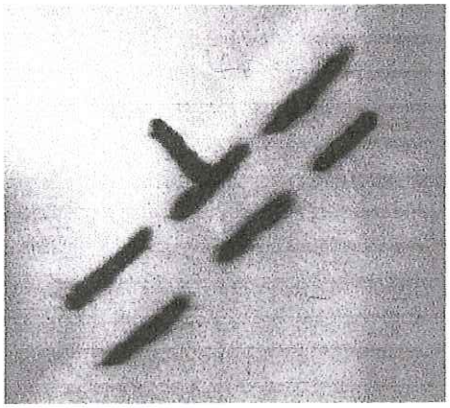

Figure 4. Sketch of a cold-cathode Penning ion source sketched on a restaurant paper napkin by Bob McPherson of National Semiconductor

The next day we built an ion source using an exact copy of the sketch dimensions and it worked pretty well. Roger (Bastide) spent the next six months trying to improve on it, but he could never better the cocktail napkin design. Bob decided to buy our first unit, which was extremely risky for him. He had concluded that buying an available safer post-analysis machine from Accelerators Incorporated would leave him as a "nobody" in National, but if the pre-analysis design actually worked, he would become a hero. And so, we had our first sale.

The name Extrion first appeared publicly, along with our ion source assembly exhibited on a table-top display, at the 2nd Conference on Ion Implantation in Semiconductors, Garmisch-Partenkirchen, Germany, in May 1971 (Fig 5).

Who's NEW in

ION

IMPLANTATION?

We are!

MANUFACTURERS OF MACHINES FOR PRODUCTION AND RESEARCH • HEAVY ION SOURCES • SCANNERS AUTOMATIC CYCLING WAFER CHAMBERS

For further information contact:

extrion
CORPORATION

PO BOX 805 · PEABODY, MASSACHUSETTS 01960 · PHONE (617) 532-2750

Figure 5. The first announcement of Extrion implanters at an ion implantation conference in Garmisch, Germany in 1971.

The cold-cathode source consisted of three concentric tubes; the center tube was raised to 2kV and the source gas, boron trifluoride (BF_3), phosphine (PH_3) or Arsine (AsH_3) was fed into its center forming a plasma between its tubes. BF_3 was unpleasant, but the other gases were extremely dangerous. (Phosphine is similar in toxicity to phosgene, the battlefield killing gas used in World War One). Although safety was even then of great importance, it took many years to perfect a furnace which could vaporize solid phosphorus and arsenic and displace the use of these extremely hazardous gases.

After extraction from the source at 30 keV, the ion beam entered a 90-degree magnet which focused the beam on a small resolving aperture. This entire assembly was mounted on three inexpensive ceramic power line insulators, after home-built insulating glass stacks consistently failed. Power to the source and magnet in the HV terminal was provided through a commercial high voltage transformer and the settings were adjusted through motor-controlled lucite rods.

One early mistake was to display the acceleration voltage in two ways: one on a meter attached to the power supply, the other in a numerical readout on the mechanical dial used to raise and lower the supply voltage. These two readings could never be synchronized and their difference caused great distress. After a short time, the mechanical display was removed. Much of this, although totally original at the time, will be familiar as standard practice today.

After analysis, the beam was accelerated to its desired final energy through an insulating tube which had its origins in HVEC designs. Prior to the wafer-holding end station, the beam passed through an electrostatic focusing lens and a beam scanner, which through a triangular-wave generated voltage, spread the beam evenly across the wafer. The scanner also incorporated a beam diverter which removed neutral particles from the ion beam before they could destroy the beam uniformity at the wafer. By switching this deflection voltage "on" to start an implant, and "off" to end an implant, the deflector voltage was also effective as an beam gate.

Finally, the ion beam, typically less than 20-microamperes, made it to the wafer. Although a threshold shift dose on a 3-inch (75 mm) wafer could be achieved in minutes, newer applications and larger wafer sizes demanded higher beam currents. Once again, our experiences at HVEC came to the rescue. Harry Freeman, who had been a technical advisor on the HVEC isotope separator while working at Harwell, had developed a multi-species high-current source using an incandescent tungsten filament to ionize the source plasma [5]. Geoffrey Ryding, who had developed a friendship with him, suggested to Peter that using the "Freeman Source" would be an assured way to increase the beam current and keep ahead of competitors. This was done and variants of this ion source are still in use today.

It's hard to believe now, but we often measured the beam dose uniformity by implanting a thin sheet of clear plastic, such as mylar. The discoloration caused by the ion beam gave an immediate visual indication of dose uniformity (or early on, of dose non-uniformity). We also used a five-cup Faraday array, one cup in each corner and one in the center, to measure the scanned beam current uniformity electrically. Use of more accurate methods, such as mapping sheet resistance uniformity in silicon test wafers were a decade away from those early days.

Another key issue in the emerging IC fabrication industry was substrate handling. Peter early realized the importance of automated wafer handling and that the end-station design was of profound impact on the overall machine performance [3]. Wafer sizes in 1970 were primarily 2-inch and 3-inch (75mm) although 4-inch (100mm) wafers appeared soon after. IBM became a significant and reliable customer, but they used 3¼ (82mm) and 4¼ inch (106mm) wafers - apparently this provided them with extra patent protection for their devices - which greatly complicated our manufacturing procedures. (Separately, IBM decreed that all equipment had to be built using metric standards. This meant that many standard purchased components, such as oil diffusion vacuum pumps and gate valves had to be attached to manufactured metric parts using metric-to-standard transition plates).

In 1971, the typical device line width was 10-micron, about the size of a large dust particle. This meant that wafers could be handled with tweezers and were allowed to slide during loading and unloading.

Our earliest automated wafer loader was a ring which held 200 2-inch wafers, each-hand mounted onto a thin aluminum platen. (Fig 6) [6] . The ring was then loaded into a circular chamber; after pump-down, each platen was moved into the implant position, implanted and moved back onto the storage ring.

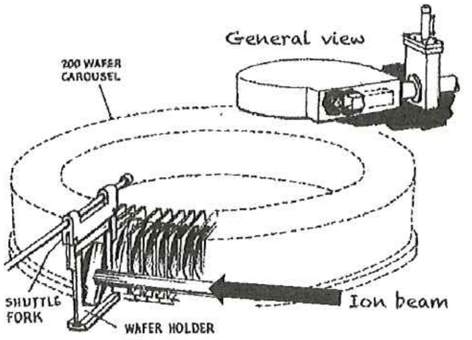

Figure 6. Sketch of the initial Extrion automated wafer handler for 200 2 inch wafers [3].

Although it was used internally, this design was never sold because cassettes used in the industry standard delivery box held 25 wafers and manufacturers did not want to wait for 8 lots to accumulate before implanting them.

Peter soon recognized that the end-station needed to resemble a Kodak slide projector but operating under vacuum, so the next version followed this understanding. It consisted of a linear platform holding 25 wafer platens, hand-loaded into the end-station chamber which was then pumped down. For implantation, each wafer platen was moved sequentially in and out of the ion beam. After 25 wafers were implanted, the end-station was back-filled with dry nitrogen and the platens were removed. Clearly, this system was not sufficient for high-volume production, so a design using entrance and exit vacuum locks was implemented to move the linear platform

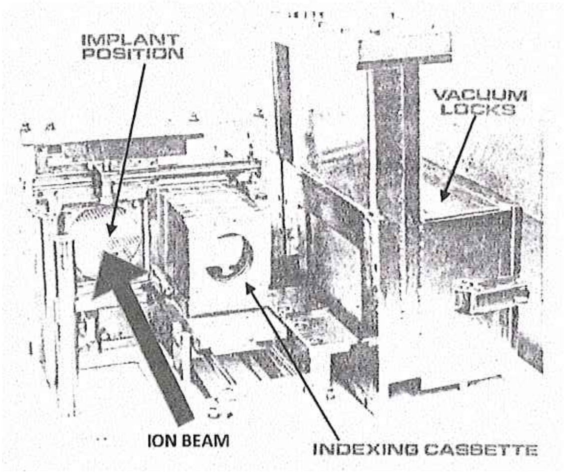

Figure 7. Components of the first Extrion production wafer loader, designed for 3 inch wafers (Model ES-30/25C) [6].

into, and out of, the vacuum chamber without breaking its vacuum. (Fig 7) [6]. For the first time, an operator could load the implanter, walk away from it and return at a known time later to collect a finished implanted batch.

By 1975, wafer handling had evolved so that individual unmounted wafers, drawn by gravity from an industry-standard cassette, moved through single-wafer vacuum locks in and out of the implant beam (Fig 8) [7, 8]. End station design continued to evolve as line widths decreased - by 1985 the line-width had been reduced to 1-micron - and manual wafer handling with tweezers and particles produced by sliding waters had to be eliminated.

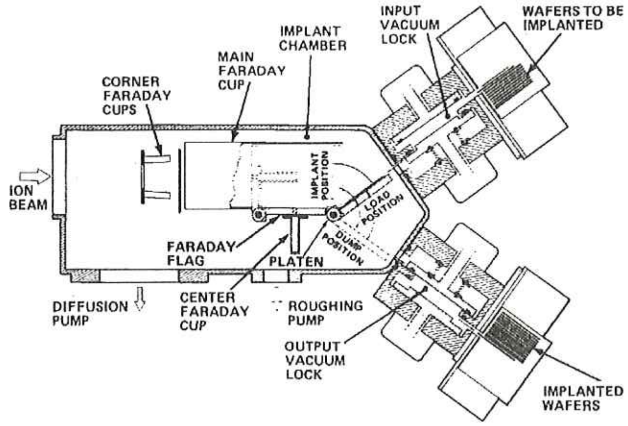

Figure 8. Diagram of a "Wayflow", a gravity drawn wafer loading system, with single wafer load locks [7.8].

The earliest Extrion implanter (Model 150) which supplied ion beams up to 150 keV, was soon replaced by a 200 keV system (Model 200-20A) which also incorporated the cold cathode source. Soon after, Extrion introduced the Model 200-20AF with a Freeman source that delivered beam currents up to 250-microamperes. This design and its later variants were, for many years, successful as industry standard tools (Fig.9).

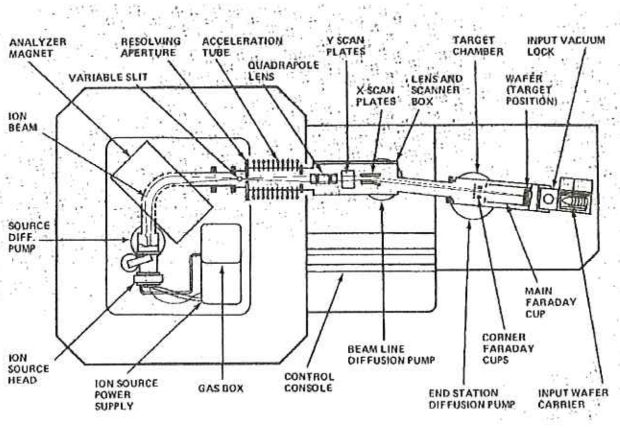

Figure 9. Layout of an Extrion 200-DF4 (circa 1984). The end-station is shown with entrance and exit vacuum locks.

An elegant boron-only machine, operating up to 100keV was made available for a short time. Unfortunately, its limited energy range and a propensity of its specially designed wafer hander for crushing wafers prevented its widespread adoption. Only one unit was sold and the machine was discontinued.

The critical 90-degree ion filter magnet was initially designed by the East Coast expert from MIT, Harald Enge. Unfortunately, ray tracing modeling was in its infancy and the calculated focal length of the delivered magnets was not often accurate. Later the West Coast expert from Stanford, Hilton Glavish, was able to increase ray tracing accuracy and his designs are still in use today.

Early magnets were made locally by a HVEC graduate, Hugh Quinn. They worked well enough but looked home-made, a sloppy mess of copper coils encased in viscous goop. Another early venture initiated by Extrion's needs, ANAC (later Buckley Systems), was recommend to us by Glavish. ANAC made beautiful looking, accurate magnets and after 1976 all of Extrion's magnets were made in New Zealand, shipped to the USA first by sea and later by air. Because of its success with implanter magnets, Buckley now is one of the largest manufacturing companies in New Zealand.

Similarly, Extrion's influence extended in other areas. For instance, early homemade high-voltage power supplies regularly failed, particularly after a spark. Then in 1980, Kaiser Systems, later to become a multimillion dollar business, was formed by an Extrion former employee and thereafter power supply reliability was greatly improved. Also, in a different setting, smaller semiconductor manufacturers such as Mostek survived (at least for a while) because Extrion implanters drastically increased the yields of their MOS devices.

V – BUSINESS ISSUES

After 18 months in business, Extrion was ready to ship its first machine to National Semiconductor. It weighed about a ton. There was no loading dock, so how were we to get our machine onto a truck? We got the solution from the leather factory next door. Their operators, adept only at lifting cowhides, tried their luck at lifting our implanter. They positioned forklifts on either side of our valuable, wonderful machine and lifted it up until the machine was just above the level of a waiting flatbed truck. The truck backed up underneath and, with great care, the machine was lowered to safety. Only then were we able to breathe again (Fig 10).

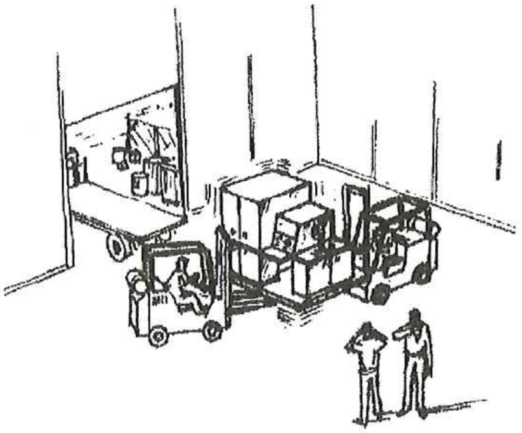

Figure 10. Sketch of the drama of lifting the first Extrion unto a flatbed truck for shipping to California by using two forklift trucks.

Soon after, implanters were shipped regularly; initially in the USA and to Europe, but then in quantity to Japan through our distributor, Marubeni Hytech. When Peter arrived in Tokyo for the first time, he decided to take a short walk even though he was really tired after the long trip. He left his hotel to walk around the block, but after four left turns he was not back at his hotel. Cleverly, he chose to retrace his steps, but that didn't get him back to his hotel either. He had decided to take a taxi back when he realized that he'd forgotten the name of his hotel. Showing his usual determination, he made it back an hour or so later.

At this early stage, one delightful feature was that all negotiations, including the price, was done scientist-to-scientist; purchasing was only brought in to sign the contract. This ended by the early 1980's as ion implanters became a standard feature of semiconductor manufacturing and purchasing agents, then as now, greatly increased the complexity of all negotiations.

To our surprise and pleasure, implanter sales rapidly exceeded the optimistic forecast presented in the business plan (Fig 11). The machine to National Semiconductor was sold for $64,000 (about $410,000 today). With the addition of some very necessary additional features, such as gate valves over the oil diffusion pumps, the price rapidly rose to $95,000 ($530,000 today). The price was based on the cost of materials plus labor but failed entirely to consider the value added to the semiconductor manufacturer! Unfortunately, this low pricing plagued the industry for years until it was corrected by Applied Materials when it entered into the high current market place in the mid-1980's.

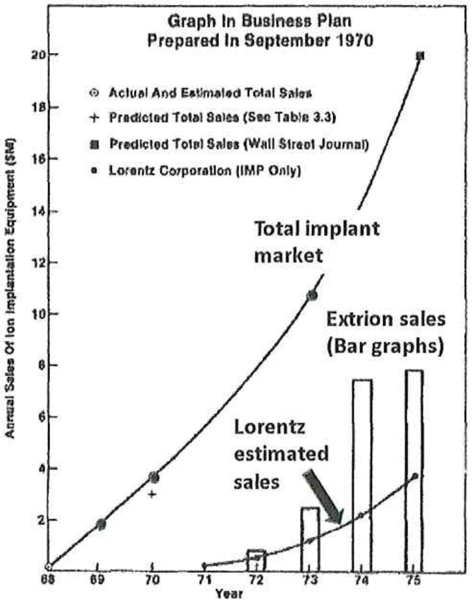

Figure 11. Extrion sales exceed expectations. A page modified from the Lorentz/Extrion business plan showing estimates and actual total implant market and Extrion (as bar graphs) yearly sales.

An anomaly by today's standards was our choice of employees. The first was Ed Warnock who had just been released on parole for breaking and entering. He seemed smart and eager, so Peter hired him as a floor sweeper and general handyman. Maybe Peter thought that if he was on the payroll and given a key to the building, he would not need to break into it. Ed rose through the ranks as we grew, and finally became the head of electrical assembly supervising forty assemblers. Two other important early hires were Bruce Libby and Marvin Farley, both of whom had training in the US military. Not one of these three would have been considered for these positions in today's world since none of them had a college degree. In general, we often found that the most productive employees came from trade schools or the armed services rather than from the universities.

Throughout the early months, we all had been working very long hours. Our families must have suffered but we barely noticed it. As in most start-up companies, people work insufferably long hours without complaining, but it often causes great stress on marriages, not unusually causing them to collapse. Fortunately, all of ours hung together but the stress was palpable. We worked seven days a week and every evening for the first year; we only cut back to five evenings a week plus Saturday morning in the middle of our second year.

After a couple of years, we reached a measure of success; the leather company space became inadequate and the smell of rotting cow skins was just too much. Gloucester Engineering, our parent company, built for us an extension to their building in Gloucester, MA and we happily moved to much more suitable surroundings.

As Extrion sold more and more machines, the cash strain on Gloucester Engineering to sustain its own growth became intolerable and the president of Gloucester Engineering decided that he had to sell their overly successful subsidiary. Since Gloucester Engineering knew nothing about the semiconductor equipment business, Peter became their key source and intermediary; he suggested they consider Varian Associates, a first-rate technology company based in California with deeper pockets. Unfortunately, despite his technical skills, Peter was a poor business man and the sale went through without any financial compensation for his achievements or for those of his team. In fact, Peter's only consideration was to continue our daily work-time fun, albeit with a more financially able partner.

We started our new life in 1976 with Varian in control. They brought in their management to help us together with exotic new tools such as inventory control and production engineering. This new large bureaucracy involved us in endless meetings, reports and controls. We entrepreneurs hated it, even though it was not only reasonable but absolutely essential for our growth which by then had grown to 1500 employees.

VI – A NEW VENTURE: NOVA ASSOCIATES

When Varian decided not to fund development of an entirely new type of ion implanter, a high current machine with up to 10-milliampers of beam current to be used for new applications such as source/drain doping, Peter began to think of leaving. Then when Peter was replaced as CEO with a more experience business executive, Bill Bottoms, Peter decided to leave, find a new partner and start all over again bringing with him crucial colleagues from his existing team.

Dave Hopkins, who was on a mission to raise the technology profile of Cutler-Hammer, a hardware company based in Milwaukee, was introduced to Peter. After a few weeks of intense negotiations, Peter and Andrew were asked to come to Milwaukee for dinner with executives and seal the deal. It was a long way to go for dinner, but it was worth it and, in 1978, Nova Associates was off and running, albeit as a start-up of the Cleveland company, Eaton Corporation, which had just bought Cutler-Hammer.

After nine months or so, we were close to having a working prototype of our radically new and different high current implanter. It was an exciting time but not without its problems. Certainly, we were unpleasantly surprised when we received a summons from Varian accusing us of stealing their trade secrets and instructing us to appear in Salem District Court a week later. We called our Boston-based lawyers who told us that this was serious stuff and that we could be closed down forthwith. A week later we sat at the back of the courtroom watching the proceedings unfold. The judge asked the Varian lawyer what trade secrets we had stolen. The first round went to us when the lawyer said he could not speak openly of the secrets because if he did, they would no longer be secret; laughter erupted in court. But that was not the end of it, although we had avoided a pre-emptive shutdown.

Then Varian made a strategic mistake! In addition to Nova associates, they also added Eaton to their lawsuit. Now, instead of swatting at the Nova fly they were opposing the Eaton elephant, a company with seemingly unlimited resources. The next step in the lawsuit was the taking of depositions. For three months, every morning at 10:00AM, our side and their side would sit in a down-town Boston lawyers' office, answering any and all questions under oath with an official stenographer recording the proceedings. Surreally, it was Norman Turner, our personal friend, who was the chief technical representative for Varian; we would face each other in opposition during the day, then meet for drinks together in the evening. When it became our turn to question Norman on what was the established state-of-the-art when we left Varian, our lawyer took an unexpected direction. His first question was: "Is this case about "ion implantation"? When Norman answered "Yes", he asked Norman to define each one of those two words. His definitions brought in new words and expressions, each of which required a lengthy definition of its own. After three months of this, Varian gave up and we all went back to work. In actuality, we had taken nothing belonging to Varian except our knowledge, but without the backing of a company as large as Eaton, the suit would have bankrupted many a start-up – as was intended. After it was all over, only the lawyers were the winners to a grand sum of about $450,000 ($1M today).

Over the next few years, Eaton/Nova grew successfully. Nova Associates' first Model NV-10-80 was an entirely new design able to deliver a greatly increased ion beam current reaching 10 mA (Fig 12).

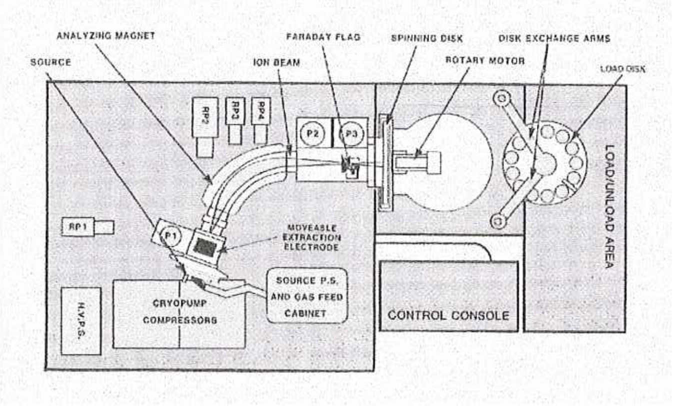

Figure 12. System diagram of the Eaton/Nova NV-10-80 high current implanter.

For high-current beamlines, space-charge forces are a major issue, both at the ion source extraction region and throughout the beamline to the wafer. With a beam power of 2-kilowatts, wafers could no longer be implanted one at a time and an entirely new style of end-station had to be developed; the solution was to mount wafers as a "batch" on a rotating disk. Under Peter's guidance, the NV series of high current implanters became the industry standard tools, just as with the decade earlier DF-4 medium current tools at Extrion.

Figure 13. A happy moment. Photo of Andrew Wittkower, Peter Rose and Geoffrey Ryding in an Eaton/Nova brochure (1986).

By the year 2000, however, Eaton realized that high technology did not match well with its main heavy industry business focus and the implant group was spun off to become Axcelis Corporation which remains a highly successful ion implanter company.

Today, the semiconductor industry has expanded greatly from its early roots. Ion implantation has long been a standard feature of semiconductor manufacturing with close to ten thousand implanters in use around the world. Ion implantation became the key enabling technology for half a century of Dennard scaling with controlled shrinking of CMOS channel depths with the combination of precise doping in the channel region and ever-shallower junction depths for source/drain junctions [9]. Ion implantation continues to be a central tool for fabrication for doping and materials modification with up to 80 distinct implant steps per advanced IC device.

Modern implantation machines differ from earlier versions mainly in the software driven control systems and in wafer handling, which has become extremely sophisticated and efficient. Throughout these changes, Peter Rose's innovative design concepts remain at the core of these new models.

VII – PETER ROSE'S WIDER IMPACTS

Following his time with Eaton, Peter's entrepreneurial talents came into play once again as he became the founder or director of many other start-up companies. These include Sumitomo-Eaton-Nova (Japanese implant manufacturer); Zymet (implantation into metals); Ibis (silicon-on-insulator); Krytek (aerosol cleaning); Epion (cluster ion beams); Implant Services (ion implantation); Orion Equipment (implantation equipment); Ion Beam Technology (ion microscopy); Niton (spectrum analysis); Micrion (electron beam technology); Passport Systems (radioactive material detection). With each of these companies, Peter was able to use his status in the industry and personal skills to help raise funding, and then give direction to these innovative endeavors.

VIII – PERSONAL NOTES

We end with some personal notes. When we first knew him, in the 1960's, he was enthusiastically athletic. He was a member of the Union Boat Club and he often spent a Saturday morning sculling on the Charles River in Boston; later he loved sailing his 18-ft Hobie catamaran at high speed and on one hull across Lake Sebago in Maine. He was also an enthusiastic skier; on one occasion, while giving a technical paper to an international audience in the Alps, he wore his ski boots at the lectern so that he would not lose a single moment on the slopes. Nearer home, he applied these skills to water-skiing.

In all the years we knew him, Peter never raised his voice in anger, even when he came across, embedded in a design, his pet peeve: the "set-screw." Every day, he arrived at work with a myriad of ideas and innovations; those which were useful were often applied the same day. His style of management was to work alongside his crew, urging us on to longer hours and greater effort. He had an infectious sense of play, a dry wit and a calm understanding of his place in the world. He was always ready to raise a glass in celebration even for a minor success. He was fun to be around and was universally liked, even by his competitors. We miss him.

Acknowledgements

We are pleased to thank Michael I. Current for archival materials and for editing and formatting this paper. We also thank Cheryl Mazer for her skill in editing the draft materials.

References

[1] Peter Henry Rose. Obituary ; Physics Today, 71 (2018) 63.

[2] G. Dearnaley, J.H. Freeman, R.S. Nelson, J. Stephen, "Ion Implantation", North Holland, (1973).

[3] P.H.Rose. "History of commercial implantation", IIET-1984, Nucl. Inst. & Meth B6 (1985) 1

[4] L.Wegmann. "Historical perspective and future trends for ion implantation systems", IIET-1981. Kingston (1980); Nucl. Inst. and Meth B6, (1984) 1-6, also see: L. Wegmann "The historical development of ion implantation" in "Ion Implantation Science and Technology", ed. J.F. Ziegler, Academic Press (1984) 3-49.

[5] J.H. Freeman et al., "Implantation Machines", Proc. of Conf. on Ion Implantation, Reading (1970), also see: J.H. Freeman, "Canal rays to ion implantation: 1886-1986", Radiation Effects,100 (1986) 161-248.

[6] G.Ryding and A.B.Wittkower, " Industrial Ion Implantation Machines" IEEE Trans. on Manufacturing Technology, Vol. MFT-4, 21 (1975).

[7] A.B.Wittkower. "Wafer Treatment Apparatus", US Patent # 3,901,183 (1975). A.B. Wittkower and G.Ryding, "Isolation Lock for Workpieces", US Patent #3,954,191 (1976).

[8] G.Ryding, A.B.Wittkower and P.H.Rose. "Features of a High Current Implanter and a Medium Current Implanter", J.Vac. Sci. & Tech. 13, 1030 (1976).

[9] R.H. Dennard et al., "Design of ion-implanted MOSFETs with very small physical dimensions", IEEE J. Solid-State Circuits, vol. SC-9, (Oct. 1974) 256-268.

ANDREW B. WITTKOWER

Andrew Wittkower's career has taken some unexpected turns. After his initial attempts (while at the Cavendish Laboratory in Cambridge, UK) to understand nuclear physics failed, he turned to atomic collision physics and was granted a PhD from University College, U. of London. He then began his first career as a research scientist, by joining a wonderfully innovative group, led by Prof R.J. Van de Graaff and Dr. Peter Rose, at High Voltage Engineering Corporation in Burlington, MA. While there, he published over 100 papers in scientific, technical and popular journals on ion sources and charge-changing collisions in tandem particle accelerators.

His second career, which lasted 20 years, was as a manufacturer of ion implantation equipment. In 1970, Wittkower, Rose and four others founded Extrion Corporation, which designed and built the first production ion implanter. Now Applied Materials/Varian, this company presently employs more than 1500 people in the Cape Ann area of Massachusetts. The presence of these people and their families has changed, for better or worse, the economic basis of the region from fishing to technology. Subsequently, Wittkower became the Founder and/or President of Nova Associates (now Axcelis), Zymet, ASM Ion Implant, High Temperature Engineering and Superior Design – all manufacturers of semiconductor fabrication equipment. For these achievements, Andrew Wittkower (together with Peter Rose and Roger Bastide) was honored with the 1986 SEMMY Award by the Semiconductor Equipment Manufacturers International (SEMI).

Subsequently, Andrew Wittkower entered his third career, fabricating and promoting a new semiconductor material – Silicon-on-Insulator (SOI). In 1986, he became a Founder of Ibis Technology, the first commercial manufacturer of SOI wafers. In 1992, he was a Founder of Soitec USA (a subsidiary of Soitec S.A in Bernin, France) which is now the largest producer of SOI wafers in the world. He remained its President until 2005 when he became President Emeritus.

He is a Life Fellow of the IEEE and a Fellow of the APS and Inst of Phys (UK).

GEOFFREY RYDING

Geoffrey Ryding has been involved with the commercial use of ion beams throughout his career. It started in 1963 with the study of charge exchange collisions of protons using an experimental 500kV Van de Graaff at University College, University of London. He was awarded a Ph.D. for this work in 1966.

After graduation he joined Peter Rose's development group at the R.J.Van de Graaff Laboratory of High Voltage Engineering where he worked with both positive and negative ion sources as well as measuring charge exchange cross sections for numerous heavy elements.

In 1970 there was a fast growing interest in using ion implantation for the doping of semiconductors and he joined Lintott Engineering to lead a group that was developing an early high current ion implanter. This work was based largely on technology that had been developed at UKAEA Harwell.

In 1973 he rejoined his former colleagues, Peter and Andrew, at Extrion to help develop the family of medium current implanters. (200-DF4 etc.)

Extrion was acquired by Varian associates (now Applied Materials) and in 1978 he left to form Nova Associates (now Axcelis) with Peter Rose, Andrew Wittkower and George Swanson where his focus was on developing the NV-10, the first mass produced high current ion implanter. In 1979 he was awarded the SEMMY by the Semiconductors Manufacturers International (SEMI) for his work with ion implanters.

From 1992 to1998 he was CEO of Ibis Technology, a company that was using intense beams of Oxygen and the SIMOX process to produce SOI wafers. He was co-chairman of the IIT Conference in 1992.

In 1998 he founded Orion Equipment to develop a new family of implanter end stations for single wafer processing of 300mm wafers. The company was acquired by Applied Materials in 2002 and he remained as General Manager of the group until 2008.

Since that time he has been involved in a number of start-ups, all requiring intense beams (>50mA) of protons with MeV energies. The most recent company, Neutron Therapeutics Inc., has developed a proton accelerator (50mA at 2.6MeV) which, in conjunction with a Lithium target, is producing neutron beams for cancer therapy (BNCT).