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Opinion paper

Michael Hatzakis, semiconductor industry pioneer

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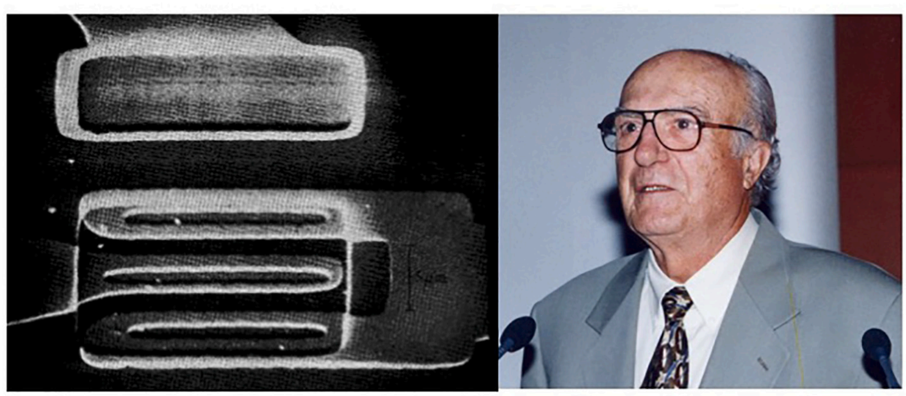
ABSTRACT

Although this opinion paper tracks the career of Mike Hatzakis (as he liked to be called), and explains the impact he made on the IT industry, it is not intended to be comprehensive insofar as the work that was underway during his career is concerned. Thus, the intent is not to cite all relevant work in the field of Semiconductor lithography, where Mike made such an impact, but to provide a historic and human perspective of this remarkable man from the land of the Minotaur (Crete) and his career, the work he championed in his labs in the US and later Greece and his very human approach to science, technology, and to people.



A 1 micron transistor built by Mike Hatzakis
and IBM colleagues in 1971
Transistor reprint Courtesy of IBM Corporation ©

1. Introduction

Mike was born to a wealthy family in Crete, whose fortunes took a turn for the worst when Mike was 11 years old. The cause seemed to be his father's involvement in a card game that went south, causing his mother and 6 siblings to become homeless.

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Luckily the Hatzakis' family ability to adapt, enabled their mother to find work and lodgings in support of the family. The brothers Hatzakis, wasted no time either, finding a way to patch into the local electricity network to power their lodging, developing their first technology experiment and learning the dangers of exposed wiring.

The German occupation created other possibilities for experimentation, including deconstructing armaments and extracting the contained explosive materials, which Mike explained, had a rod-like structure and would burn very rapidly when ignited. His curiosity seemed boundless. If only his mother knew….

As in every single part of his life, Mike managed to befriend everyone, even the occupying German soldiers, trading motor cycle and radio parts for cigarettes. With schools under occupation, this was his classroom and his trading post. He and his brothers, taught themselves how to build motor cycles, radios and even constructed a film projector viewing old film reels disposed by the Germans.

On completion of high school, Mike moved to Athens, opened a radio sales and repair shop while also acting as an ambassador to a US mission in Greece. It was probably this "ambassadorship" that opened his eyes to opportunities in the US. He moved to New York in the 1950's to start a business and support his family in Greece, from funds generated from his work repairing radios and TVs. After some time, the small shop he worked for was absorbed into the famous Collins Radio corporation while Mike was completing his college and master's degree at night at NYU, over an eight-year period.

His studies resulted in a career which started at the IBM Corporation's Research Centre in 1961 and it would take another 'mere' 28 years for him to launch his next career at Demokritos in his beloved Greece, where he founded the microelectronics laboratory and where he taught. One of his close colleagues, Alec (now Lord) Broers explained Mike's almost innate ability to understand technical systems:

> "*Mike was one of the cleverest men I have known and his immense talent for understanding difficult problems and finding ways around them was quite remarkable. I recall him telling me about his early days in New York before he joined IBM, when he was repairing TVs and radios; fixing those complex devices. I asked him how he managed without having the circuit diagrams and manuals for them. He just smiled and explained that it was usually clear to him where the problem was likely to be and he just probed around changing things until he found the problem.*
> *Mike's talent was broader and more universal and at IBM he demonstrated this by making the most advanced semiconductor chip devices in the world. This was not a lone activity. Advances in high technology invariably involve many different skills and disciplines and Mike was a warm and considerate person who had the ability to work with people. Everyone liked him and enjoyed his cheerful personality and engaging sense of humour. He was also persistent and did not give up until he had made things work. Advancing technology involves solving hundreds, even thousands of problems and Mike's record was second to none.*
> *As part of an IBM business, Mike knew that the benefit was in making electronic devices smaller and he pursued that goal. He was always brilliant at cutting through the confusion making things simple and making them work*".

1.1. Early IBM career - building the world's smallest structures

One of Mike's earlier publications was "Two Interconnection Techniques for Large-Scale Circuit Integration" [1], which instead of using mechanically positioned metal lines, showed how photo and electron beam lithography could be used to fabricate small features. Integrated circuits had been patented in 1959, but the idea of this paper was to reduce the features of the interconnect and to go beyond the contact mask and subtractive etch processes. This work could not have been completed had not Richard Thornley brought the first sub-micron e-beam system to IBM.

Shortly thereafter, Mike and two of his friends, Srini (R. Srinivasan) and Ivan (Ivan Haller) published an insightful and practical paper in the IBM Journal of Research titled "High-resolution Positive Resists for Electron-beam Exposure" using a variety of polymers which were irradiated with both electron and photon beams [2]. Their notion was that if the electron beam could break down the polymer chains they had just placed on a silicon wafer, it could be used as an image forming layer for lithography (see Fig. 1). Coating was ingeniously simple. One placed a drop of the polymer dissolved in a suitable solvent, placed the wafer on a spinner and at 1000 rpm or so, the solvent would evaporate leaving a few thousand Angstrom thick film to be tested.

Using the electron beam to degrade the polymer length and to then dissolve the resulting lower molecular weight material leaving a pattern (hole) in the irradiated areas is now a standard approach in electron beam lithography. It is not clear where Mike acquired two large drums of two different molecular weight DuPont poly-methyl methacrylate (PMMA) powder that weighed around 10 lbs. But it was this material that was used to develop the smallest features in the world from the work of Broers [3], to that of many others in the lab that pushed the limits of resolution, e.g. the work on ultra-short channel Si FET circuits [4]. These legendary containers probably still reside somewhere in the Watson lab and were the sole source of PMMA for decades, when it was called upon to provide the highest resolution electron beam patterns.

Alec Broers and Mike worked together on a large number of projects. The results [5] that they published describing the work that focused on patterning for integrated circuits, won the best paper award at the National Electronics conference. In 1969 they showed how the electron beam system that Broers had built, with a spot size of 3 nm, could be combined with the advanced lift off techniques that Mike had developed using PMMA, to create extremely small metal structures. The structure and size of these features were far in advance of their time.

The same approach [6] enabled the two authors and Eric Lean, a surface wave device expert, to build a 1.75 GHz acoustic wave transducer that was the first sub-micron electronic device ever built. They were even contracted to sell these devices to MIT Lincoln Labs. A publication in Industrial Research magazine in 1970, which had a very broad readership resulted in a lot of attention, as the results

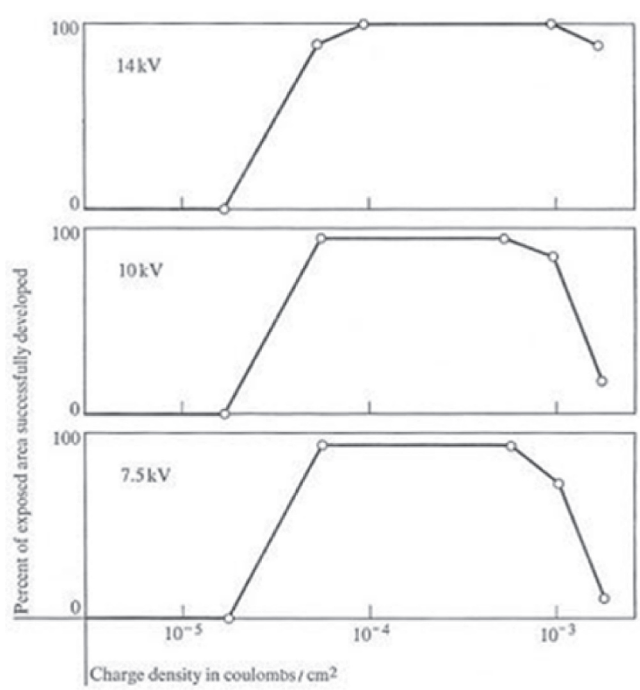


Fig. 1. Exposure characteristics of poly-(methyl methacrylate) positive resist. Adapted from ref. 2, Reprint Courtesy of IBM Corporation ©.

demonstrated the creation of wires some 0.1 μm wide at a time when features in devices where many tens of microns in size.

Fundamental to the philosophy of IBM's Research laboratory is the ease with which individuals from many different domains can collaborate. Rewards came from patents and publications, but the ultimate recognition was when the work resulted in improved products or globally recognized scientific accomplishments. It was and still is an outstanding place to work because of the people that inhabit the Watson and the >10 global labs who focus on science that is relevant to IBM's business.

One of the important consequences of the work related to electron beam exposure of resists, was the discovery, that upon sufficient irradiation with electron beams, it was possible to create re-entrant resist (in this case PMMA) profiles. Until that time, patterning metal required wet etching which because of the isotropy of etching limited the gap between lines to the thickness of the metal. What Mike and his colleagues discovered [7] was that re-entrant (basically overhanging) profiles of the exposed layer, allowed metal to be deposited into the opening, while sitting on the unexposed resist. A solvent would then be used to dissolve the unexposed resist, thus lifting off the sheet of deposited metal, leaving it in the exposed areas (see Fig. 2). Lift- off techniques enabled much higher metal interconnect densities that helped propel the device revolution.

In 1970 Luby Romankiw, who became an IBM Fellow [8] in 1986, two years before that honour was bestowed on Mike, came to Mike to see what could be done to increase disk recording density. In contrast to other approaches, Luby (actual name Lubomyr, who was also the head of Ukrainian Scout organization in the US) was concentrating on plating disk drive heads in a thin 3 μm thick film. Between Luby, Mike and Ian Croll they built drive heads that were 2.5 μm thick and had 2 μm wide gaps. Using e-beam irradiation [9] and Shipley 1350 resist for the recording gaps and plating under a magnetic field resulted in these tiny features.

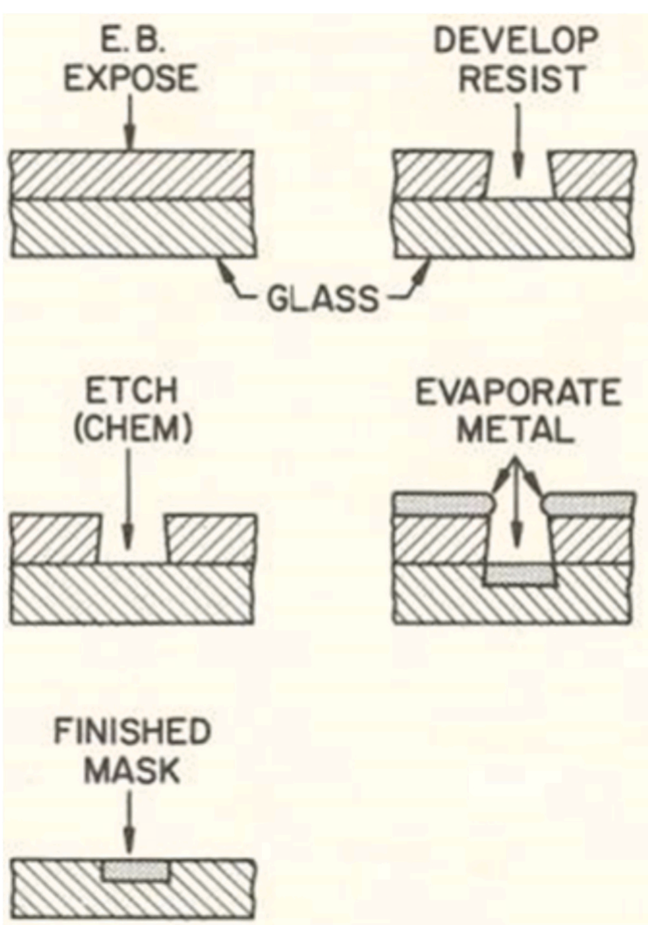


Fig. 2. The first lift-off process. Adapted from ref. 7. Copyright 1969, ECS.

This was a revolutionary approach at that time. Existing techniques required 30 μm thick permalloy that was wet etched, resulting in at least 30 μm gaps. The heads that Romankiw et al. were fabricating were at least 1 order of magnitude smaller than the existing heads. It was this kind of experimentation and approach that helped to create today's Terabyte drives, where the use of read-write heads that fly above a disk platter has been likened to flying a Boeing 747 six inches off the ground [10].

As Alec Broers explained earlier, it was Mike's gregarious character and understanding that "smaller was better" that enabled him to easily work with the very talented, and sometimes quirky researchers that worked in the Watson Labs, discovering new approaches which Mike would apply to his adopted field of lithography.

While every lab today that is involved in semiconductor patterning, probably has a scanning electron microscope (SEM), this was not always the case. It is interesting to read what Oliver Wells, the pioneer of scanning electron microscopes, grandson of author H.G. Wells, wrote in a chapter on the history of the SEM [11], quoting Mike's understanding of the importance of the instrument. Note that this cross-sectioning technique described below became useful for many other purposes.

"It was the visit to Ken Smith's SEM in Montreal that triggered the idea for cross-sectioning the wafer in order to observe electron penetration profiles in resists. This in turn led to the development of a number of significant processes including the electron beam fabrication of devices and the lift-off metallization technique. It also provided a considerable boost to the study of fast electron energy deposition in solids both experimentally in the SEM and using computer simulation (Monte Carlo simulation), a science that has generated many hundreds of papers and PhD theses over the years."

Although Mike was very focused on his research, he would often leave the building for a walk around the employee gardens with employees and friends, tear at something from the plants and say "here try this". Invariably it would have a flavor of some kind. He knew his plants and his lithography equally well. We always managed to avoid the occasional belladonna that would be growing in the boundaries of the property.

Because electron beam patterning was evolving, Mike decided with some friends, to build an electron beam column whose acceleration voltage could be altered in the several kV range. It was directly coupled to an optical rasterizer which would use the signal from a photomultiplier which monitored the light intensity as it scanned over a black paper mask. An interruption of the light beam would interrupt the electron beam as it scanned in a raster fashion synchronized to the optical rasterizer. Using this system, Mike and his colleagues built 1 μm bipolar devices with a peak gain-bandwidth product of 5 GHz, which was a significant accomplishment at that time [12].

Mike worked with a number of people to build this resist exposure system including Richard Thornley who together with Al Speth designed and installed it. It became Mike's workhorse on Aisle 17 on the 2nd floor of the T.J. Watson Research building. The back side of the lab contained fume hoods and chemicals used to coat wafers and subject their coatings to a broad range of lithographic processes.

Later e-beam systems in IBM's labs included Vectorscan, that a very close friend and colleague Philip Chang [13] worked on and Hontas, a shaped beam production patterning tool built at an IBM production facility by a team led by Hans Pfeiffer [14], were much more sophisticated in their exposure capabilities and throughput. But there was nothing to beat Mike's e-beam column whose main focus was to determine whether a material could be used as an electron beam resist or not in minutes.

Mike would often take newly exposed resist material and test a variety of solvents on it to see if the exposed image would be revealed with a solvent. He would emerge from the darkened room with a pair of magnifying lenses on his head and say “Look at this” or “I have to show you something” and we would be off, testing a new class of material for the “right properties”.

1.2. Creating devices for new technologies

The search for smaller devices continued with the work that another industry pioneer, Bob Dennard led, to build a high-density memory array based on FETs and proceeded to do so with Mike and others providing the lithography [15]. This was a test using PMMA as an etch resist for wet chemical etching of the very thin layers and lift off for metallization. It demonstrated how far the single transistor memory cell could go at that time (1973).

Notably, at that time IBM was focusing on the use of bipolar devices to build its profitable mainframes. But the work that Dennard and others in IBM who focused on CMOS, saved IBM when in the early 1990’s it became impossible to drive enough power to the bipolar devices nor cool them while accomplishing the necessary performance. Without that work, IBM would have been unable to stay in the marketplace [16,17]. Bob Dennard had a lot to do with the persistence of CMOS focus at IBM and as is now acknowledged was the originator of the single cell memory device that is still used in CMOS memory today. We should not miss to mention here that Bob Dennard passed away on April 23 of this year (2024).

In the mid 1970’s a number of technologies which promised to provide improved processor speed and storage emerged. Those too were subject to the need to reduce dimensions and Mike was called on again to see how far Josephson [18] and Magnetic Bubble devices [19] could be shrunk using the e-beam column and PMMA, at a time when IBM was looking beyond semiconductors to create new logic and memory devices.

Mike became a manager in the mid 1970’s and some of the first members of that group included a technician, Ben Canavello, who was a very kind ex-military technician, and a young scientist named Jane Shaw.

As much as e-beam lithography enabled the fabrication of small features, industrial volumes of devices were generally fabricated using UV exposure, chromium on glass masks and a photoresist. Many commercial photoresists were based on diazoquinone based compounds dissolved in a novolak resin. Exposure to UV, produced an acid that rendered the exposed areas soluble to alkaline developers. But under e-beam vacuum conditions less acid is produced reducing the resist sensitivity. Since diazo-type resist offer process compatibility on manufacturing lines, Mike’s team worked to identify the most sensitive diazo resist systems for use in both e-beam and the commonly used Perkin-Elmer “micralign” systems that exposed the resist to UV radiation.

In 1978 Jane and Mike published a paper focused on the comparison of a number of positive resists subjected to photo and e-beam irradiation [20] identifying key parameters of resist performance to be characterized enabling IBM’s fabs to optimize their systems for maximum yield.

These results were used by other members of the group including Jones and Paraszczak, to build the 1st 3-dimensional resist development simulator [21] that was prompted by the work of Neureuther and Dill at UC Berkeley [22] and others.

Simultaneously, in the late ‘70s the necessity to reduce metal linewidth and provide highly integrated metal lines drove a research effort to develop a “lift-off” process for metallization using the typical ultraviolet sensitive diazo resists used in manufacturing.

The successful PMMA “lift-off” developed by Mike for mask making in the ‘60s for e-beam production of masks, could not be used due to the insensitivity of PMMA to optical wavelengths and therefore impractical for commercial use.

To answer this need Ben, Jane and Mike developed a simple surface treatment which “hardened” only the surface of a diazo-type photoresist film after UV exposure creating an undercut profile [23] after image development. Metal was then “lifted-off” after evaporation through the resist stencil (see Fig. 3). This simple process could be used with the UV sensitive resists and optical lithography tools used in manufacturing. It was an important discovery that was used in the fabrication of memory devices at the facility in Essex Junction VT but was phased out after a few years due to environmental concerns of the surface treatment.

1.3. Developing 2-layer resist systems

One day around 1980, Mike walked out of his lab, saying that he found something interesting, starting the group’s effort on silicon resist systems. His insight led to the first publication of an organosilicon polymer utilized as a radiation-sensitive oxygen plasma barrier layer [24].

Nobody in the lab had any experience with silicon-based polymers, but at the time there was a large focus on what is called 3-layer imaging systems [25]. Here a lower organic layer was deposited, on top of which a middle thin layer of oxygen plasma impenetrable material would sit below a third thin imaging layer which would act as a mask while the intermediate layer was eroded by a halogenated plasma. The idea was that using a thin dielectric such as sputtered silicon dioxide, and patterning it using a thin photoresist and a halogenated plasma, would faithfully transfer the pattern from the thin patterned dielectric to the underlying thick organic layer using an oxygen plasma.

Clearly this required a complex material set with issues of stress cracking, interlayer adhesion, chemical compatibility etc. complicating the efficacy of the system. If instead it were possible to create a spin on material, which was resistant to an oxygen plasma and could be imaged in a thin layer (<2000 Angstroms), this would deal with many of the issues outlined above.

Mike’s hiring of a scientist who had fled from the Soviet Union, a certain Edward Babich, who was an expert in a novel area for IBM Research - organosilicon based polymers, led to a new area of Research for the group. This was a strategic move since as mentioned before, Mike’s discovery of the utility of silicon-based polymer as an imageable barrier layer led to the use of these polymers in lithography.

Not only was Ed a world class synthetic chemist, he had a sense of humour as big as himself and was accompanied by his wife Inna, a son and daughter and a dog called Clipper. Clipper would evolve from a sedate and loving cocker spaniel into a paroxysm of barking when asked what he thought about the Soviet Politburo. How they were all able to escape from Russia without being detained, speaks to their fortitude and understanding of how to deal with an intrusive and brutal system. And how to adapt, with humour.

Ed suggested the use of a number of silicon-based materials which by themselves might be sensitive to electron beams and photo-irradiation. One of the first easily accessible polymers that was chosen was polyvinyl siloxane. It has an exceedingly good e-beam sensitivity and was highly resistant to an oxygen plasma. This means that there was no need for a 3-layer complex system, all that was required was a thin (~1500 Angstrom) layer of poly vinyl siloxane and after e-beam imaging and development, the underlying hard baked organic layer (usually a novolak based photoresist like Shipley AZ1350) could be readily patterned with an oxygen plasma. A comparison of the various processes was published in an SPIE publication and helped to open up the field of oxygen plasma-based patterning [26].

Further, a publication by Mike’s team led by Jane Shaw and including the newly arrived Ed Babich demonstrated that some of these polymers were not only imageable by e-beams but also by deep UV (2537 Å) thus began to demonstrate their promise [27].

As mentioned earlier, IBM Research contained skills from every domain and the desire to understand how the seemingly very flexible and fluid silicone polymers survived the onslaught of an energetic plasma brought a surface science expert Ned Chou, Ed and Jurij together. The strangest part of the encounter was the first interchange between Ned, who was born in mainland China, and Ed was partly

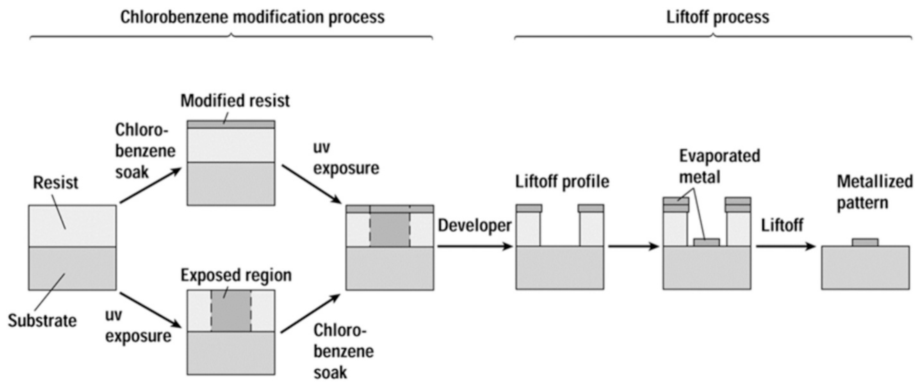


Fig. 3. Process sequence for a lift-off operation. Adapted from ref. 23, Reprint Courtesy of IBM Corporation ©.

spoken in Russian since the Communist parties in both countries were closely connected and the Chinese population was taught some Russian. This team's data showed [28] that the oxygen plasma treatment of the poly dimethyl siloxane created a structurally strained layer of silicon oxide (with an unclear stoichiometry) some 1 nm in thickness which receded slowly in the plasma due to sputtering. Initially we tried to coat a layer of poly dimethyl siloxane (PDMS) film with Shipley 1350 resist to create a 3 layer test system and found that the top layer would not adhere to the underlying siloxane film. It was then discovered that even a very short oxygen plasma processing of the PDMS would instantly improve adhesion of any additional resist. Clearly adhering to the plasma formed oxide layer of the PDMS.

1.4. Generating revenue from research

As always, Mike was not just interested in understanding these materials for scientific insight, rather he wanted to see them deployed into real products. Because of Mike's network around IBM, we were often introduced to groups that turned out to teach us the realities of production. Working with Brian Grenon who was the engineer responsible for the mask house in Essex Junction, VT and who until this day is still a consultant in this field, we deployed PDMS for production mask-making using ebeam irradiation. Brian now also grows grapes for wine, but that is another story and in a different state.

Armed with this knowledge, we decided to investigate the performance of a wide range of silicon-based polymers. The workhorse of photoresist, the diazoquinone was combined with a polysilicon polymer to create diazopolysiloxanes. The PDMS maskmaking process now had a negative tone optical resist process where required, which also used the same hard baked AZ resist as the oxygen plasma eroded masking layer.

A group including Ed, Jane, Mike, Ben Croll and Jurij were given an award for this work and shared it with our Mask House colleagues, whose management had somehow decided not to do the same for their contributions.

The PDMS polymer provided another unique capability since it could act as a probe for energy deposited in it. Together with a group of individuals with widely different backgrounds including, Dieter Kern, Mike Rosenfield, Mike Hatzakis, Jurij Paraszczak, Jim Bucchignano and Ed Arthur, an intern, we embarked on a process to better understand where electrons went when they irradiated a layer of resist sitting on a silicon wafer.

It is well known that a high energy beam (e.g. 25 keV) of focused electrons deposited only a fraction of those electrons in these thin (1 μm and less imaging layer) and most of them recoiled from the silicon wafer thus were redistributed by backscatter. Although the incoming beam of electrons could be focused down to a few Angstroms, once those electrons hit the silicon wafer they would be redistributed in a roughly Gaussian cloud which was several microns in diameter. This exposure by backscattered electrons, coined the proximity effect, caused innumerable problems if the resist did not have sufficient contrast.

The team studied the growth of a ¼ micron wide line created with a dose just sufficient to cross link the PDMS resist atop the underlying organic material some 1 μm thick, The beam was scanned to form the ¼ micron line at varying doses ranging from 0.4 of the nominally required to write the line to 120× that dose. What this did was to show the evolution of the line with dose. By writing a whole series of patterns with one beam one could map the actual deposited energy [29]. This was the first time anyone had been able to actually measure the total forward and backscattered electron beam. Experiments were performed at different electron beam acceleration potentials and it became clear that with a 2-layer resist of this kind 10 kV acceleration was much more preferable to 25 kV, which is where most e-beam systems set the acceleration voltage at that time.

Ed led a study of a range of silicon containing polymers including polysiloxanes, polysilmethylenes, polysilazanes, polysilanes, polysilphenylenes, and organic polymers with side silyl groups. The simple etch monitoring tool, which comprised a laser interferometer that looked at the reflectivity of the polymer surface provided a surprising amount of useful information. Given the refractive index of the material, we could then determine the polymer etch rate in the plasma.

In all, some 15 different materials were tested for oxygen plasma resistance and sensitivity to electron beam radiation. We concluded that pendant groups had a strong effect on cross-linking and that the methyl group was very important in this regard [30] as was the total silicon content as related to resistance to oxygen plasma etching. Our group was very focused on characterizing the features of these polymers and reviewed much of their work in Microcircuit Engineering journal.

Ed's arrival in the lab resulted in a number of new directions. One was in the field of high rate organic polymer etching. The challenge with current plasma systems was that they could be extremely useful for transferring a thin pattern to a thick underlayer, but the speed with which this was possible left much to be desired.

We now had developed expertise in silicon polymers and reactive ion etching plasma systems that led to the use of PDMS (poly dimethylsiloxane)resist for e-beam mask fabrication but a multi-layer resist system was needed for logic chip personalization which were fabricated using a diazo-type UV sensitive resist systems. Line width control was an increasing problem caused by (a) non-uniform thickness over topography, and (b) exposure dose variation due to differences in surface reflectivity. Additionally, multilayer systems offered increased resolution and wiring density when patterning only a thin photoresist layer over a thick planarizing layer.

The team (Ed, Dave Whitman, Jane and Jurij) investigated both UV sensitive siloxane polymers as reactive ion etch barriers as well as processes that would incorporate silicon into diazo- resists used in manufacturing. As introduction of a new resist into manufacturing was a daunting process, we concentrated on trying to modify diazo resist, with silicon containing liquids that would react with the resist film.

One that was at hand was HMDS, hexamethyldisilazane. This liquid was commonly used as an adhesion promoter and coated on the surface of a silicon wafer just before the application of the resist. It had been noticed that after the development of the resist image there was a very pesky film that was left on the surface that was difficult to remove even with plasma etching. Silicon had been incorporated by the photoresist at the interface by a reaction of the phenolic resin with the HMDS. We initially attempted immersing a diazo resist into HMDS which resulted in its resistance to an oxygen plasma. Many other silylation agents were tested, finding that HMCTS (hexamethylcyclotrisiloxane) suggested by Ed provided optimum RIE resistance. Together we optimized the optimal conditions for imaging processing.

Scott Jacobs, an enthusiastic manufacturing engineer at the IBM East Fishkill plant, helped deploy this process in manufacturing, resulting in improved logic chips for IBM's mainframes.

1.5. Packaging, polymers and plasmas

Layers of materials in semiconductor chips are rarely above a micron in thickness. In packaging, thicknesses and features can be 10× larger and consist of structures placed under the chips providing electrical access. An IBM mainframe contained printed circuit boards, some 3 ft × 3 ft square with many wiring layers. To these boards an array of soldered copper/glass-ceramic blocks with 120+ layers of wiring were soldered, atop which the chips were attached. These were monumental feats of engineering, which not only had to survive large thermal excursions, but had inherent stresses in them due to thermal coefficient mismatches. Polymer layer coating ceramics were 5–25 μm thick and required patterning.

Mike had heard of microwave plasmas somewhere, which claimed that they could strip polymers at very high removal rates above 1 μm/min. This resulted in the creation of IBM's 1st microwave plasma reactor, which Steve Dzioba from Bell Northern, in Canada [31] helped with.

John Heidenreich, a graduate from UC San Diego joined our team, rapidly developing tools to analyse plasmas. This included measurements of plasma density, plasma potential and their functional dependence on many parameters. A lasting relationship with colleagues at the University of Montreal including Prof. Michel Moisan and his student, Gaston Sauvé. helped us considerably in dealing with the analysis of plasmas. Our understanding of the mechanisms of etching, anisotropy and capability was significantly enhanced by our collaboration and led by John's work [32].

At this point the multidisciplinary group that Mike developed had expertise in the chemistry of materials for lithography, a deep understanding of their response to irradiation of different forms, their ability to be shaped and used as masks and their interaction with plasmas. We also had a group of individuals who worked well together and shared time together. All of this had gradually evolved under Mike's guidance as though he had planned the path all along. Which he probably had. As has been mentioned many times before, Mike had an instinct for making things work together and he always seemed to know what was missing, before anyone else did. In any other age, he would have been a mythical person.

Mike left IBM in 1989 to start a new career by building a microelectronics research center in Athens at the National Center for Scientific Research, named "Demokritos", with a very clear idea of its direction as judged by the projects which evolved.

1.6. Creating a leading center of silicon technology in Greece

In 1988, Mike was elected as the inaugural director of the Institute of Microelectronics (IMEL) at the National Center for Scientific Research (NCSR) Demokritos (www.demokritos.gr). Later IMEL was merged into a newer Institute of Nanoscience and Nanotechnology INN (www.inn.demokritos.gr). Prior to this role, he spent a sabbatical year at Demokritos in 1985 while on leave from IBM, during which he played a pivotal role in establishing the equipment infrastructure and clean room facility.

At IMEL, Mike Hatzakis established a new group focused on Lithographic Materials and Processes, including Pattern Transfer, comprising enthusiastic Post Docs primarily recruited from overseas and Ph.D. students. Notably, he continued to support their research through his own grants until they secured their own funds and permanent positions at Demokritos, which significantly contributed to the Institute's future development.

The initial research efforts concentrated on high sensitivity e-beam lithographic resists, resulting in IMEL's first participation in a major European project (FREE). Additionally, the collaboration with Dow Chemical, marked the Institute's first project with a leading chemical company, targeting the modification of chemically amplified epoxy resists to enable aqueous base development for e-beam lithography.

Simultaneously, the development of a novel e-beam lithography simulation software commenced, eventually becoming the Institute's maiden commercial product. Furthermore, the exploration of newer lithographic processes, such as wet silylation (see Fig. 4) and dry development, introduced a novel research direction at IMEL [33].

Mike successfully procured the necessary equipment to outfit the newly established clean room, thereby providing the infrastructure for cutting-edge research, firmly positioning Greece on the semiconductor map. His multifaceted approach to patterning materials and processes laid the groundwork for establishing IMEL as a globally recognized center of excellence. It was two decades ago that Mike and coworkers were concerned about aqueous development of crosslinked negative tone photoresists with a eye on sustainable lithographic processes [34].

1.7. Extending the impact at IMEL

The addition of new researchers covering various key areas further solidified IMEL's reputation. Participation in international projects such as the EU based NANCAR and ADEQUAT, collaboration with the ETEC company, and the publication of significant papers bolstered the group's standing. Moreover, the successful organization of the MNE conference in Athens in 1997, overseen by Mike and his team, attracted 700 participants worldwide, including Nobel prize holder Heini Rohrer [35], significantly raising the profile of both the Lithography and Pattern Transfer Groups and IMEL's research efforts.

Mike, was distinguished by his sharp wit which was, however, very discreet. He never imposed his views or ideas, but in his kind way showed the way one might follow a specific approach. Interpersonal relationships have always been of great importance to Mike. Our group at the Institute grew after 1990 when he had also been settled permanently in Athens in a house with a unique view of the Aegean Sea.

Mike's office was always open and he always made sure to leave in public view outside his office many journals and conference proceedings such as MNE and EIPBN. Of particular note was the permanent availability of the Bridge magazine issued by the US National Academy of Engineers of which he was an elected member.

This open attitude has helped all of us to have access to new trends and ideas in science and technology at a time where the Internet could not help much, as it was still in its infancy. Overall, the strong influence of Mike's charismatic personality enabled the foundation of a world recognized Microelectronics center at NCSR Demokritos.

1.8. Working with people and technology

Why Mike chose a given material, why it worked without spending lots of time in library stacks looking at a broad range of papers from well-established chemists, was always a mystery. But just as in the repair of radios and TV sets, Mike had an instinct in his approach to materials and systems. He just did it and that was a part of his success and what drew others to collaborate with him.

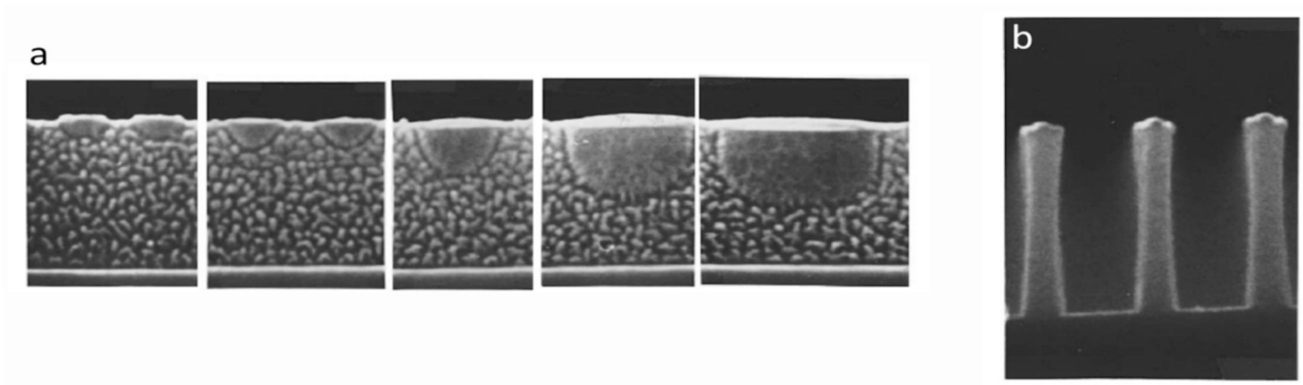


Fig. 4. Oxygen plasma colored SEM profiles of silicon uptake after DUV exposure and silylation. From left to right 0.25, 0.30, 0.5, 0.8, 1 mm lines are shown (a). SEM pictures of 0.25 μm resist lines after dry development (b). Adapted from ref. 33. Copyright 1996, AVS.

Mike was aided and abetted in his social environment by his wife Mary, a gregarious and welcoming individual who was always ready to help others and have fun. Thanks to her and Mike's social skills, they would often have gatherings of people from every level of the IBM hierarchy at their home in Chappaqua NY. Sometimes, new employees would approach the front door and be greeted with some variant of "Hi, welcome, I'm Mike a Cretan and this is my wife Mary, who is a Lesbian". Which was almost true. Mary's family hailed from Lesbos as Mike's hailed from Crete.

These gatherings in the US were full of laughter, where people would learn about Retsina and where guests would bring food from their own countries. The Watson lab was full of people from every corner of the globe and the Hatzakis dinner parties would reflect the polyglot nature of these cultures. It was here that people also became lifelong friends. Here we also got to understand a little of what our senior management really thought and here it was where told them why they may need to adjust their notions. Mike and Mary made everyone at these gatherings feel like we were part of a big Greek family. Some even got to learn a few steps from the Sirtaki which ultimately turned out to be similar to steps from dances from other countries.

We also fondly recall the gatherings at his home in Athens, reminiscing over the abundance of French wines graciously shared through his generous hospitality. Sadly, he endured the unexpected loss of his first wife Mary during a cruise in the Aegean, followed by the devastating loss of his beautiful home to fire. Yet, in a testament to his resilience, he rose above these immense challenges, rebuilding his life with newfound strength.

In both the US and Greece, we were struck by both the simplicity evident in his daily routines and interactions with others, as well as the infectious spirit of optimism he effortlessly exuded. Coupled with his diverse cultural background, humour, and wealth of life experiences from Greece—particularly Crete—and the USA, it is no wonder that deep friendships quickly blossomed.

Mike was both a friend and a true intellectual, embracing the finer things in life such as good food, wine, spirits (especially whiskey), beautiful company, and enriching music, with an all-embracing attitude. Whether reveling in Beethoven's symphonies, Portuguese fados, or Greek rebetika, he exemplified a global citizen, relishing the exploration of different cultures through travel and interpersonal connections.

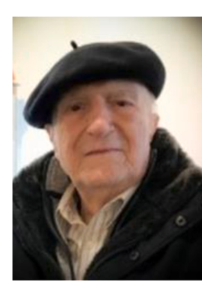
It was this attitude that led new scientists that later joined when the new e-beam system was installed at Demokritos, to combine Homer with Nanotechnology and create Homer's Iliad on a chip to be given as present to IMEL visitors [36].

Mike's intellectual prowess extended beyond cultural appreciation to encompass technology on every level. He often shared anecdotes about tinkering with his old Volvo, delving into car mechanics alongside his son Mickey. For him, the ability to repair household appliances like washing machines was as indispensable as troubleshooting the electron beam machines in the laboratory. He once humorously remarked that he spent half of his career chasing leaks in the vacuum systems of such machines, and half on a relentless pursuit of knowledge.

Under Mike's guidance, the Demokritos research team had the privilege of interacting closely with prominent figures in the field of microelectronics, including Leo Esaki, Bob Dennard, and fellow scientists from IBM's e-beam lithography group at Yorktown Heights. During this time, individuals such as Dieter Kern, Philip Chang, and Hans Luhn graciously extended their expertise to assist in installing the Institute's first e-beam lithography system, responding to Mike's invitation. Through these interactions, Mike instilled a sense of confidence in all IMEL scientists, placing their work within an international context and inspiring them with aspirations that profoundly influenced the Institute's trajectory long after his retirement. Mike was honored as an MNE fellow in the MNE 2006 conference in Barcelona, and he continued to support the conference for its second edition in Athens in 2008.

His enduring mantra, "there is 'nothing we can't do' but only 'things we don't want to do'," remains etched in our minds, serving as a constant reminder of his unwavering determination and good humour. For another decade, we had the privilege of his presence at the Institute, and subsequently, almost every summer in Athens at his new seaside residence with his beloved second wife Denia. There, we continued to bask in his humour, and glean wisdom from his experiences.

For a short farewell for Mike see the INN webpage "Farewell to a pioneer of Microelectronics and Nanotechnology: Honoring Michael Hatzakis who passed away" [37].



Mike Hatzakis with his signature beret at age 93.

Not only was Mike an engineer's engineer, but he changed the world of Information Technology though his generous inclusion of others, a liberal application of good humour and a warm appreciation of the foibles and capabilities of those around him. And lest we forget, good food and wine. We are very grateful to their children Helene and Michael Jr. for their insights and gracious additions to our knowledge of Mike and we all really, really, miss him. As we read this, with a lump in our throats and glasses of wine in our hands we wish him "Γειά μας!"

Supplementary data to this article can be found online at https://doi.

org/10.1016/j.mne.2024.100276.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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